Space Communication Architecture Supporting Exploration and Science: Plans and Studies for 2010-2030

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NASA is developing a new Space Communications and Navigation Architecture enabling NASA's Exploration and Science programs to be executed between 2010 and 2030. In addition, there will be a focus on decreasing the cost of Space Operations and identifying critical technologies needed to enable future evolution of our communication and navigation (C&N) systems. The SCAWG is collaborating across Mission Directorates and NASA Centers to develop and recommend the concepts of operation, requirements, candidate architectures, technology insertion, design options, and acquisition and sustainment approaches for affordable, robust support to human and robotic missions. This paper describes the results of the efforts conducted in 2004, plans for 2005, and communication issues facing the system of systems. The top level architecture is divided into Earth, Moon, Mars, and Deep Space components. The Earth Local Network includes the evolved Space Network (SN), Ground Network (GN), Deep Space Network (DSN), and NASA Integrated Services Network (NISN). The Moon architecture includes the Lunar Local Network covering lunar surface intra-site and site-to-site relays as well as the Lunar Trunk relay to Earth. The Mars architecture is comparable. Science missions throughout the rest of the solar system continue to communicate with DSN via dedicated links. A host of candidate technologies currently in development or requiring new investment are being assessed to enhance capabilities and reduce weight, power, and cost of communications systems, subsystems and components. As part of the architecture, the plan for communications and navigation research and development investment is being developed to identify key technologies, benefits, costs, risks, and opportunities for insertion into new and evolving systems. This plan is being developed as part of the NASA Capabilities Roadmap team in concert with the Exploration Systems Mission Directorate, Science Mission Directorate, the Office of the Chief Engineer, and other stakeholders. Key technologies to implement this are discussed including interplanetary laser communications, new standard protocols, and advanced low-power avionics. The paper will also describe the processes and tools being used to determine the best architectural approaches.

I. Introduction

NASA has long recognized that efficient, high quality communications is an essential enabler for all space activities. As we embark on a new Exploration Program, and continue our current Science and Human Space Flight Programs, we must plan for the supporting communication capabilities. This will require system acquisition and technology development efforts that fit into an architectural framework for space communications. This space communication architecture must be evolvable from our present capability and matched to the needs of the emerging Exploration Program as it matures. Therefore, the Space Operations Mission Directorate (SOMD) established a Space Communication Architecture (SCA) Working Group (SCAWG) in February 2004 to develop the architecture. Membership of the SCAWG includes NASA's Exploration Systems Mission Directorate (ESMD), Science Mission Directorate (SMD), Office of the Chief Financial Officer (OCFO), Centers, and managers of SCA programs making this a One NASA initiative. The purpose of this paper is to document the status of work completed by the SCAWG through December 2004.

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II. Key Challenges and Approaches

As the SCAWG began its work it was realized that there are a number of challenges that it will face. The Working Group has identified approaches to mitigate these challenges. In this section we discuss the nature of the challenge identified and outline the approach being used to deal with each challenge.

A. Challenge: Develop the architecture while exploration strategy concepts are evolving

The Exploration Program is still in its formulation stages. However, since the communication systems that the Program will use must be in place ahead of exploration events, it is essential that a supporting communications architecture be established in the near term. This architecture must begin with the present systems and evolve slightly ahead of the Exploration Program evolution. The crucial information needed by the SCAWG can be summarized in three basic questions:

- *Where are we going?* The answer drives the architecture coverage capabilities to assure that there is adequate communication support at the locations of scientific and exploration activity.
- *When are we going?* The schedule is a key consideration in determining the evolution path for the communication architecture.
- *What will we be doing when we get there?* An understanding of the activities to be conducted at the destination allows us to determine the types of data to be sent, their sources and destinations, and approximate requirements on data rate and the numbers of simultaneous connections required.

The initial approach being used to address this challenge is to develop sets of informal requirements to be used for understanding the evolving Exploration, Science, and Operational needs. These requirements are derived from review of available information, such as pertinent Design Reference Missions (DRM) provided by the Exploration, Science and Operations Directorates and close dialogue with the Directorate representatives on SCAWG who relay the latest considerations as the mission program concepts and plans evolve. As the ESMD, SMD and SOMD Concept of Operations (Conops) and top level mission requirements in response to the President's Vision for Space Exploration[1] matures, the SCAWG will use these agency approved plans to further refine our architectural efforts

B. Challenge: Provide the architecture in a time frame enabling the required near term actions to be taken

To stay slightly ahead of the mission needs, communication system acquisition actions must be programmed early. Acquisition actions for supporting communication systems that need to be operational in the 4-10 year time frame must be considered for budgeting action in the near term. The same is true for technology investments that need to be started in support of long term infusion into the architecture. Therefore, for the early operational elements of the communications architecture to be in place at the right time, any changes from the presently planned communications program must be identified early in the architecture development effort.

The approach for early identification of any communication program changes is accomplished by establishing an iterative process for communications architecture development with an early first cycle. Therefore the SCAWG's plan for architecture development revolves around 6 month cycles or *rounds*.

The first round is scheduled to complete by the end of March 2005 and includes four major objectives:

a) Definition of the "Framework" architecture for Earth, Moon, and Mars.
b) Identification of major elements of the architecture, such as Earth-based ground terminals, relay spacecraft, and any Lunar or Martian surface relays.
c) Definition of relationships (e.g., communication links) between the elements down to the Radio Frequency (RF) spectrum level.
d) Identification of key technology work areas needed to address capability enhancements required in later stages of the architecture implementation.

A second round is to be completed by the end of October 2005 and includes:

a) Refinement of the "Framework" architecture by considering newly evolving mission concepts and plans and any new communication architecture concepts identified for further investigation in the previous cycle.
b) Extension of the framework architecture below the RF Spectrum level to define network structure and management and identification of standards to be used for communication protocols.
c) Refinement of the architecture to assure smooth evolution from one architecture stage to the next.
d) Expansion of technology work area definitions by closely analyzing the Technology Readiness Levels (TRL) and projecting TRL progression to enable infusion into the architecture.

A third round in 2006 will further refine the architecture and technology roadmaps to assure alignment with the firming concepts and requirements for Exploration, Science, and Operations.

C. Challenge: Organize a Space Communications Architecture Working Group that captures all necessary viewpoints

To successfully develop the supporting SCA needed over the next 25 years, it is crucial that the SCAWG consider all relevant viewpoints. Therefore SCAWG must represent all of the stakeholders. This includes communication users, providers, technologists, and radio frequency spectrum experts.

The organizational approach for the SCAWG is to include NASA representatives from the Centers and Headquarters Directorates that are either providing existing space communication services (e.g., the Space Network or SN, the Ground Network or GN, and the Deep Space Network or DSN) or have a stake as a developer or user of future space communication capabilities. In addition, the organization is structured to provide technical expertise through a technical assessment team that is staffed by communication experts from across the Agency. Since cost estimation is a major consideration in the evaluation of architecture alternatives, NASA's OCFO provides leadership on cost estimation methodology and a cost assessment team is focused on use of the latest NASA approved processes for cost estimation, including acquisition and use of cost estimation tools.

D. Challenge: Maintain interoperability with international space agencies

NASA has a long history of working with the International Space Community to develop interoperable space communication capabilities. This work includes both RF Spectrum level and communications protocol level coordination and collaboration as well as mission collaboration such as the International Space Station (ISS).

Since operation in the same frequency band is fundamental to interoperability, the SCAWG's approach is to ensure spectrum interoperability with other Space Agencies as a necessary check on each architecture alternative considered. The SCAWG encourages and actively supports efforts by the NASA Spectrum Manager to coordinate with other International Space Agency spectrum organizations on selection of appropriate frequencies to be used in our future architectures. As part of the next six month cycle activities the interoperability consideration will be extended to the communication protocol level by working with the various International groups that work in this area.

E. Challenge: Include Interoperability with other US government agency space communication resources

NASA has worked with other US Government (USG) agencies over the years to achieve interoperability with other USG space communication systems. For example, NASA has been apart of multi-agency efforts to provide a framework architecture that will enable NASA space communication resources to provide communication services to DoD and NOAA satellites and for DoD and NOAA space communication resources to provide communication services to NASA satellites. This framework architecture is referred to as the SATOPS architecture and its intent must be preserved in whatever future space communication architecture the SCAWG recommends (Fig 1).

The approach to preserving this architectural agreement is to invite active participation of DoD and NOAA representatives in SCAWG meetings and as independent reviewers in the Independent Review team. In addition, SCAWG membership will include NASA members of the Joint NASA/Air Force SATOPS Network Architecture and Analysis Group (SNAAG).

F. Challenge: Address both threshold and objective capabilities

The evolving Exploration and Science Programs plus the legacy Operations missions form a baseline mission set. Threshold space communication requirements can be derived using this baseline mission set. All future space communication architectures must meet the threshold requirements. However, there may be instances where, with little additional cost, added capability can be provided by making investments in technology.

The SCAWG is actively investigating capability enhancement through the use of new technologies. This is a focused effort being executed by the Technology Assessment Team. The basic approach is to:

a) Identify technology and system capability enhancement options for each architecture;
b) Conduct detailed cost estimation; and
c) Conduct value analysis for capability enhancement options.

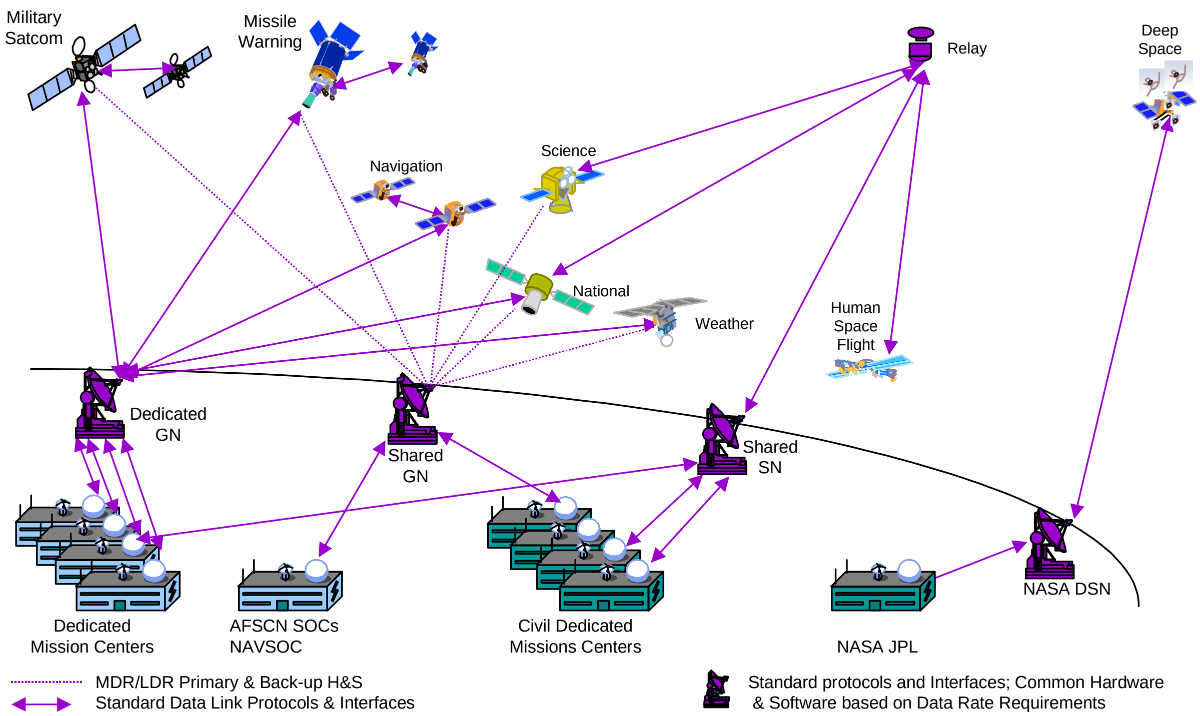


Figure 1. SATOPS Shared Ground Antennas and Space Relay

III. Architecture Definition Plan

Defining NASA's SCA for the next 25 years required performing a number of studies divided by time frame and solar system location. We designed the first round of architecting to be performed from February 2004 to March 2005. During this period, objectives included defining an architecting process, developing modeling and simulation tools or tool extensions, and training our staff in using the process and tools in addition to the primary goal of defining the SCA. Concepts and requirements for the overall Exploration System of Systems (ESS) was under development in parallel by NASA's Exploration Systems Mission Directorate (ESMD). Consequently, the SCAWG undertook development of its own operational concepts and requirements as a basis for generating and evaluating candidate architectures. From February through November 2004, the SCAWG developed its own concepts, scenarios & designs based on anticipated requirements while coordinating with ESMD and Science Mission Directorates (SMD) as much as possible. Since the release of preliminary Exploration Systems of Systems Requirements for Spirals 1,2 and 3 and the Crew Exploration Vehicle (CEV) Conops and Requirements in December 2004, the SCAWG is evolving to more direct use of ESMD and SMD products and more detailed coordination as ESMD and SMD complete their initial studies. ESMD's products to date have focused on the higher level ESS and CEV while SMD has focused on the scientific objectives of its missions. Consequently, the SCAWG still has to develop significant detail to create a picture of the communications and navigation systems and operations. Table 1 shows the current status of SCAWG's architecture definition. The SCA is being defined in five year increments

A. Processes for Architecture Definition

SCAWG's process for defining candidates architectures, analyzing the alternatives, and selecting reference architectures can be divided into the first round, currently in progress, and the follow-on round planned to start in the second quarter of 2005.

1. Round 1 (Feb 2004 – March 2005):

Initially an architecture definition process was defined based on the expectation that the studies for each time frame and location would differ sufficiently in terms of assumptions, Figures Of Merit (FOM), candidate architectures, and analyses that each study should be handled independently. This led to the process shown in Fig 2.a. In addition to the technical steps shown, each study requires management steps to formulate the study, secure resources, coordinate and review intermediate results, and conclude the study by reporting to the full SCAWG.

Table 1. Status of NASA Space Communication Architecture Definition (as of January 2005)

Time / Location	2010	2015	2020	2025	2030
Earth Network (EN)					
• Space Network (SN)	Done	Done	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development
• Deep Space Network (DSN)	Done	Done	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development
• Ground Network (GN)	Under development	Under development	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development
• NASA Integrated Services Network (NISN)	Done	Done	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development
Lunar Network (LN)	Done	Done	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development
Mars Network (MN)	Done	Done	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development
Rest Of Universe (ROU)	Done	Done	To Be Completed by March 2005	To Be Completed by March 2005	Conops & Architectures under development

Studies resulting in major recommendations affecting program requirements and budgets are subjected to SCAWG votes.

The technical approach for the time frames is divided into two parts: *projecting forward* for the near term time frames (2010-2015) and *projecting backward* from an objective (goal) Conops for the more distant time frames (2020-2030). Extrapolating for the next 10 years is based on using existing systems that are operational and reflected in NASA's program plan, or are expected to be in operation for at least 10 years. For example, the Tracking and Data Relay Satellite System (TDRSS) is currently operational and is planned to remain in operation due to replenishment satellites that are launched in the 2012-2015 time frame with 15 year lifetimes. For the far term, a vision of the objective Conops is being developed for 2030 that starts from a "clean sheet" but factors in legacy systems such as TDRSS. Candidate architectures are evaluated and a reference architecture selected to meet this vision. The intervening 2020 and 2025 time frames are defined by developing an implementation plan for reaching the objective 2030 architecture. The architecture for the 2020-2030 time frames is scheduled to be completed by March 2005 to support NASA's budget cycle and ESMD requirements definition.

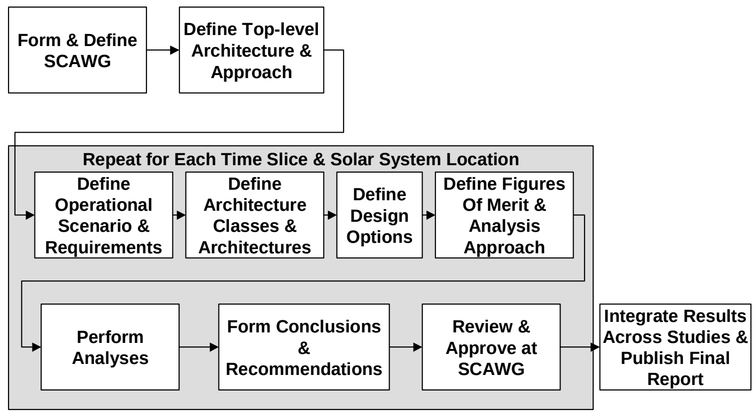
After executing the initial process across several studies during Round 1, two conclusions became apparent:

- Some elements of the process were more repeatable than anticipated. There was more carry over of assumptions, candidate architectures, analysis results, and scoring methodology than expected.
- Studies were consuming too much time and labor to complete Round 1 on schedule. Studies lasted approximately two months at a cost of 5-6 man-months.

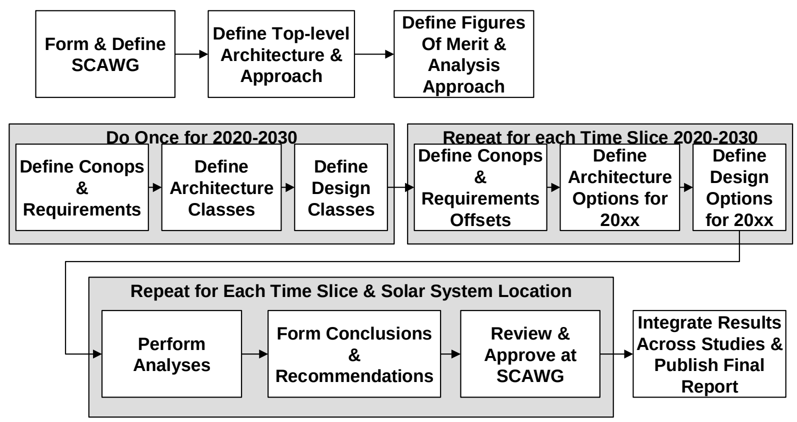
As a result, the process was refined to extract commonality that could be applied across multiple studies (e.g., lunar studies) or all studies. This resulted in the revised process shown in Fig 2.b. Integrating results across the solar system and over the entire 2010-2030 time period has not been done yet. However, the process has been started as we document the results of our studies.

2. *Round 2 (Starts in April 2005):*

Round 2 will differ significantly from Round 1. We will have a reference SCA against which to evaluate proposed improvements, technology updates, and changes in Conops and requirements. We will have most of the tools in place with a team experienced in using them. We will have a repository of information and analyses from Round 1. Perhaps most importantly, we will be more heavily engaged with our C&N "customers" (ESMD, SMD, and SOMD) in exchanging ideas and information that will enable all of us to do a better job the second time around. Thus, our Round 2 plan will repeat the studies over the time frames and locations performed in Round 1 with revisions based on lessons learned, changes in concepts and requirements, and tighter integration of the C&N Technology Roadmaps.



a) Initial Architecture Definition Process



b) Revise Architecture Definition Process

Figure 2. SCAWG Architecture Definition Processes

B. Architecture Classes and Candidate Architectures

The SCAWG is defining generic classes of architectures and specific instances of these classes for each network within the solar system. For example, Figure 3 shows the primary architecture classes defined for the Lunar Network (LN). In addition to the seven classes shown (counting the Lagrange L1 and L2 halo orbits separately), classes for the Lagrange L4 and L5 points were also defined; however, none of the candidate architectures for these Lagrange points has demonstrated enough potential value to expend study resources at this time. From the seven viable architecture classes for lunar constellations, 50 candidate LN architectures have been analyzed. For a specific study such as the lunar architecture in 2010, a subset of these candidate architectures is selected for detailed analysis in the context of the required support for envisioned scientific and exploration missions.

C. Concepts of Operation, Scenarios, and Requirements

To develop candidate architectures and evaluation criteria for each time/location study, we must create as comprehensive a picture as possible of the human and robotic mission context including related infrastructure and legacy systems. Since ESMD was evaluating concepts of operation for the Exploration program in parallel, the SCAWG was forced to develop its own conops based on available information. References [2-12] provide a partial list of sources used for these initial Conops.

Within this overall context, a specific scenario is built that focuses on the C&N aspects to help elicit performance requirements. An example scenario is taken from the LN 2015 study (Fig. 4). By 2015, human missions to the Moon have commenced and a combination of fixed base Landers, human-driven and robotic Rovers,

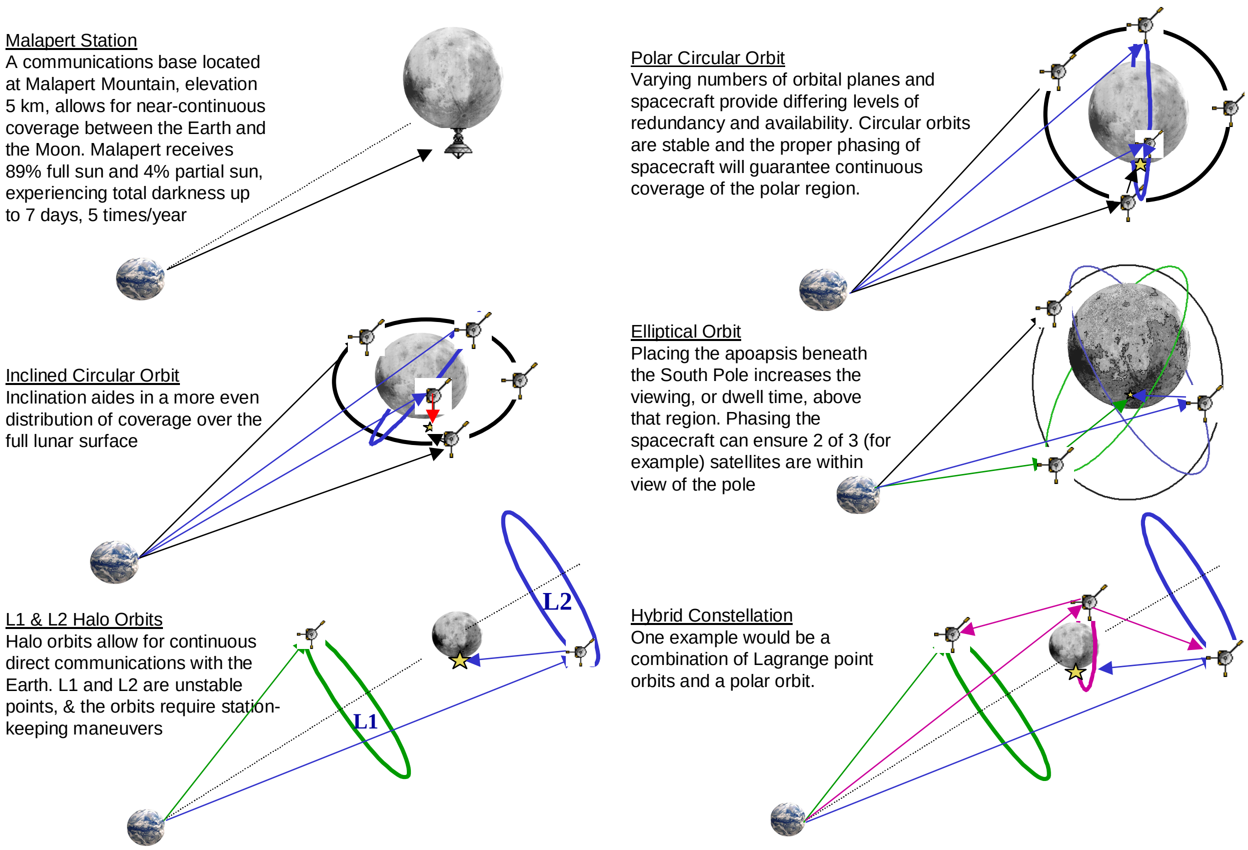


Figure 3. Architecture Classes of LN Constellations

and emplaced sensors at various locations around the lunar south polar region generate up to five 100 Mbps data streams. For the set of sensors emplaced in a particular location, a multiplexer is used to interleave the data from the various sensors. The Earth-Moon trunk link shows a total of 500 Mbps required on the return link and 200 Mbps on the forward link.

D. Designs

The scenario is then used to drive development of spacecraft designs. Several designs are developed for the candidate architectures being evaluated in the study. Designs may be developed within the SCAWG team or by requesting a contractor to generate a quick design concept based on existing buses and/or payloads. For example, the LN 2015 study generated designs for a TDRS-class spacecraft (whose communication payload design for one configuration is shown in Fig 5) for the orbiting Lunar Relay Satellite (LRS) and for the lander concept at Malapert Station (Fig. 6). The Malapert Lander is based on a Mars Viking lander base with an inflatable 200m mast from which inflatable reflectors direct beams generated by antennas on the lander base for the proximity and Space Ground Links (SGL). Mass and power estimates are generated for each design concept at levels of fidelity reflecting the maturity of the designs. For example, the mass statement for the TDRS-class concept is nearly as accurate as an operational TDRS satellite while the Malapert estimate in comparison is very top level.

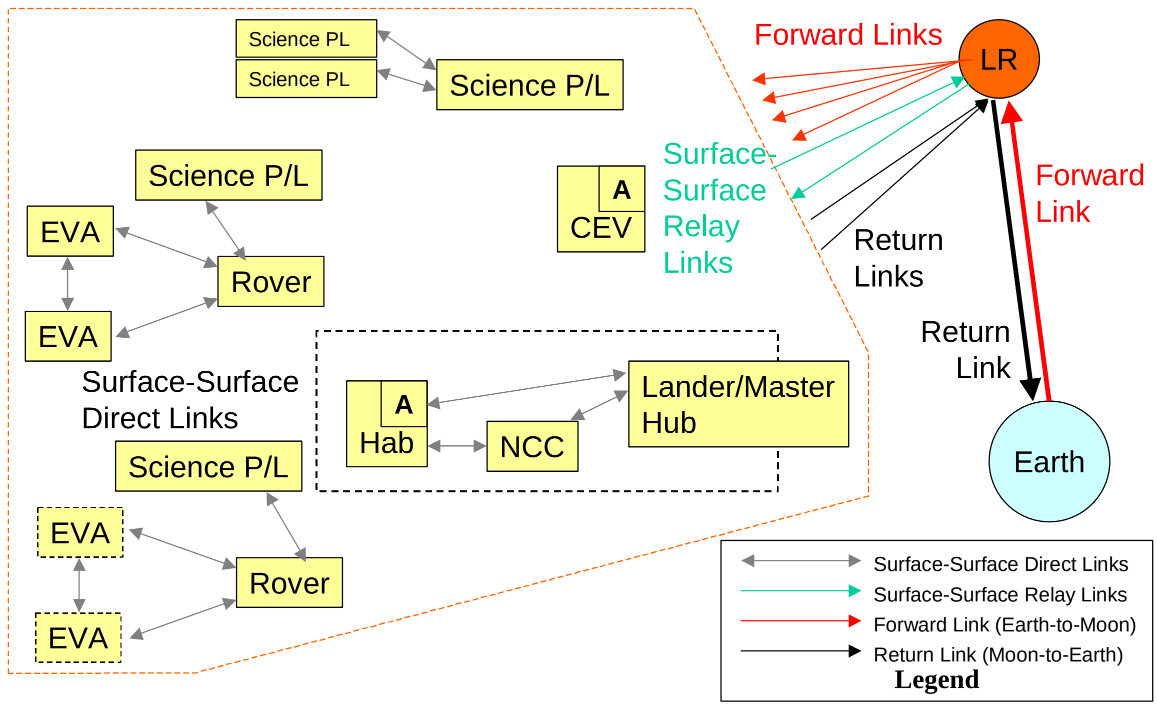


Figure 4. Example Scenario Developed for the Lunar Network 2015 Study

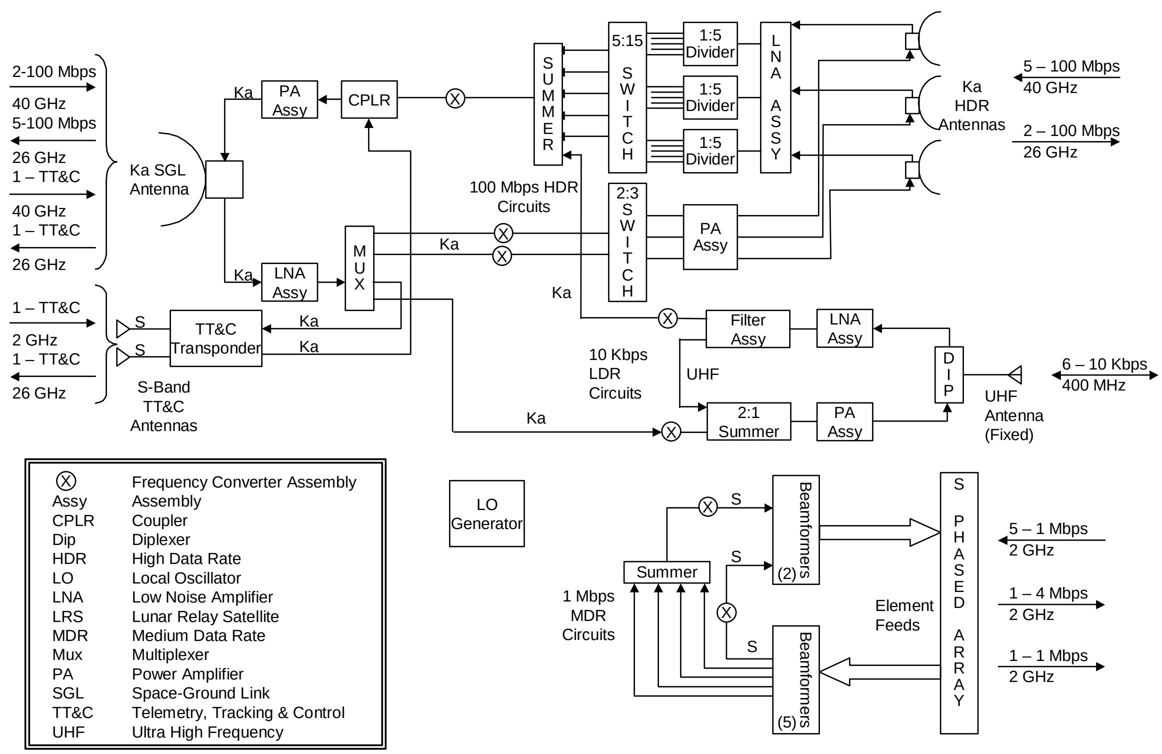


Figure 5. TDRS-class Communication Payload Design Concept for LN 2015 Study

E. Figures Of Merit (FOM)

In each study, the candidate architectures are evaluated against a set of FOMs normalized against the requirements elicited from the scenario. While the FOMs were originally expected to have some differences between the studies, the SCAWG has concluded that we can adopt a standard set usable across all of the studies.

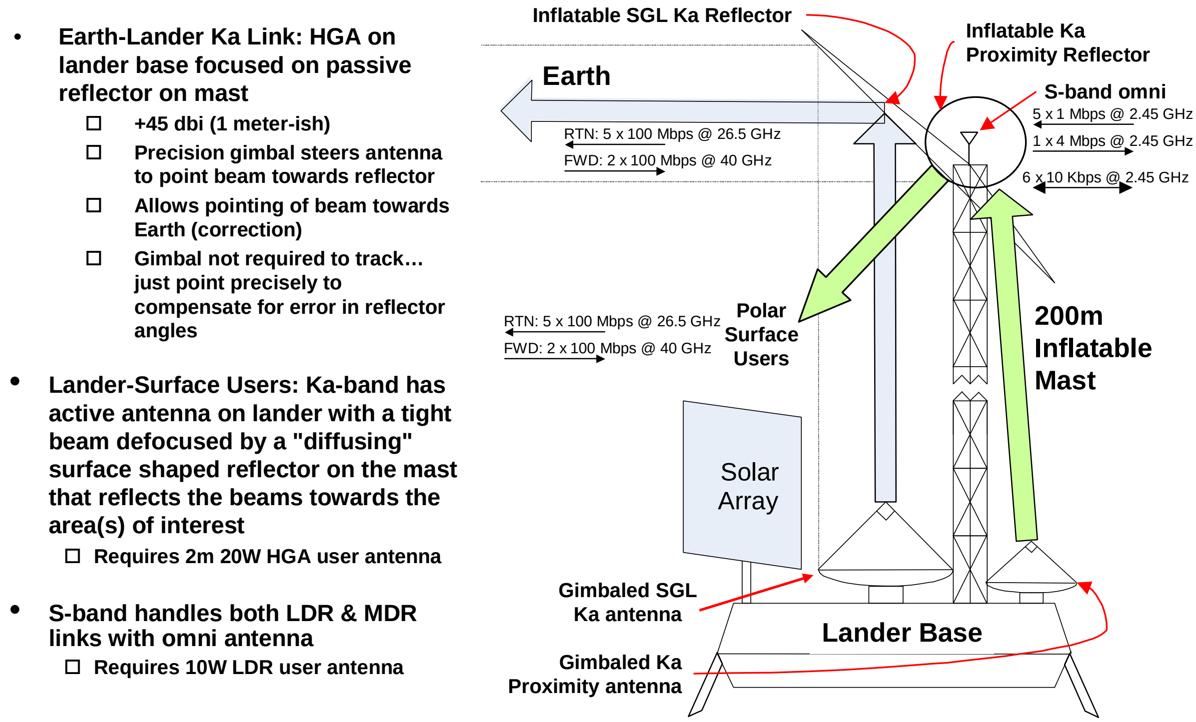


Figure 6. Malapert Station Lander Design Concept

Table 2 shows the current definitions for the set of FOMs. These definitions are still evolving. In particular, the use of GDOP for assessing navigation utility provides a dimensionless measure of accuracy due to errors in the navigation data sources that is independent of constellation altitude but does not provide an absolute measure of 2D/3D accuracy such as position knowledge. Consequently, the navigation utility FOM is being expanded to combine two measures.

F. Architecture Definition Tools

Tools used by the team can be divided into several types: orbit analysis, C&N performance analysis, cost analysis, decision support, and architecture management.

1. Orbit Analysis

Satellite Tool Kit (STK) by Analytic Graphics, Inc. is the principle tool used for defining candidate architectures, analyzing static or summary performance measures such as viewing coverage as well as dynamic performance simulations to calculate orbit stability, propellant required for stationkeeping and maneuvering, and orbit insertion. A large number of STK models have been generated. For example, 50 candidate architectures (constellations in specific orbits) were generated for the LN and modeled in STK to determine surface coverage and visibility of communication targets. For selected issues, more detailed simulations were developed. For example, for small satellite concepts with multiple spacecraft on a single Expendable launch Vehicle (ELV), simulations of orbit insertion and satellite deployment were needed to validate certain candidate orbits.

2. C&N Performance Analysis

Communication link budgets: Each NASA Center has its own tool (e.g., GSFC CLASS) for performing detailed engineering link analysis. SCAWG comparisons of results between these tools showed that they generate results that differ by as much as 3-4 dB. With detailed comparisons, these differences could be traced to different assumptions made by the communication engineers using them, different default conditions programmed into the tools, and different methods of calculation. Studies that have been done by a designated Center have employed their own tools. However, for general communication of results across the SCAWG, we have resorted to developing a simple Microsoft Excel spreadsheet-based link budget and coordinated assumptions across study teams to get results on which we could agree.

Table 2. Figures Of Merit

FOM Title	Description	Weight (100 pts)
Visibility	Composite score for 2 factors equally weighted: 1) % of time with one relay visible from the transmitting asset 2) % of time with two relays visible Note: Nominally, candidate architectures must have at least one visible relay back to Earth at all times (human mission) with a 10-degree minimum elevation angle.	19
Orbit Stability	A measure of the effort required to maintain the satellite orbits. Effort quantified as velocity change (ΔV) for a five year period.	9
Failure Tolerance	Percent visibility with 1 satellite out (= % data volume, 1-satellite-out)	11
Navigation Utility	Accuracy measured by Geometric Dilution Of Precision (GDOP) which measures impact of the spatial distribution of navigation data source errors.	8
Mission Evolvability	Ability to easily modify assets by inserting technology & modifying design to meet Exploration & Science goals from 2010-2030+. Measures the accommodations made in the design to allow future design expansion or modification to meet changes in mission needs over the potential life of the system. This is quantified by five criteria: • Programmability • Pre-Planned Product Improvement (P3I) • Open Architecture • Planned Technology Insertion, and • Planned Utilization	11
Adaptability	Measures the ability to change operations or be changed to fit changed circumstances (i.e., to handle changes in operations or support new requirements without design changes). This is quantified by two criteria: • Programmability and • Operational Flexibility	9
Link Capacity	Combination of aggregate data rate, data volume, & real-time latency	12
Scalability	Measures ability of system to expand capacity beyond initial deployment. This is quantified by eight criteria: • Ability to add satellites, • Ability to add transponders, • Ability to add frequencies, • Ability to reuse spectrum, • Ability to increase efficiency (of modulation, topology, etc.), • Ability to increase locations served, • Ability to increase data rates, and • Other growth features	8
Sustainability	Cost to replace S/C to maintain constellation for 5 years	7
Partial Life Cycle Cost	Space portion of system modeled with non-recurring DDT&E and recurring cost of flight units aimed at relative cost comparison of options	--
User Burden	Effort required by users to use communication services provided. Measured in terms of user antenna size, broadcast power, & complexity of user's communication subsystem. Note: User burden is intended to be standardized for all candidate architectures, so this FOM is used to penalize options that fail to meet the standard or reward options that reduce user burden.	5

3. Communication satellite design

One weakness of a group of communication engineers is that they are not well equipped to generate designs for an entire spacecraft bus. For the near term time frames where candidate architectures are based on existing designs such as TDRS or derivatives of existing designs, the SCAWG studies have been able to use existing design data with minimal modifications and simplistic assumptions such as prorating the size of a bus up or down to match a communication payload that is scaled up or down. Within the modest excursions in studies so far, these assumptions are reasonable given our resource constraints. However, for the time frames farther in the future, anticipated communication technologies will be embedded in spacecraft designs that reflect improvements in other technologies that the SCAWG is not qualified to design. For Round 1, we will deal with this by extrapolating existing spacecraft into the future based on historical rates of improvement in selected technologies such as electronics, propulsion, and power. For Round 2, a more robust approach will be employed.

In addition, a variety of models have been built in Excel and Wolfram Research's Mathematica to address specific analyses such as orbit determination, geometric dilution of precision (GDOP) for modeling navigation utility, and detailed link budgets that balance uplinks and downlinks while minimizing user burden.

4. Decision Support:

Part of the architecture definition process has been to establish a scoring procedure for ranking candidate architectures once their FOM scores have been calculated. Assigning relative weights to the FOMs and integrating the technical results with cost estimates and risks requires the development of a consensus heuristic value model. Two methods were evaluated for this purpose. The first method was the Value Measuring Methodology (VMM) that was developed under government contracts by Booz-Allen-Hamilton. VMM was developed to aid government decision makers in conducting cost-benefit-risk analyses that reflect the value of social and political benefits in addition to traditional technical and cost benefits. It was developed by Booz Allen and academics affiliated with Harvard University's Kennedy School of Government under contracts with the General Services Agency (GSA) and Social Security Administration (SSA). It has been applied to Information Technology (IT) and non-IT projects and used successfully for investment portfolio management as well as in program level management. The SCAWG convened a workshop on 21 October 2004 to evaluate VMM. In addition to SCAWG voting members, invited participants included NASA External Relations, Education, and Policy personnel from NASA Headquarters to widen the scope from a technical communication system perspective to include other NASA stakeholders. Booz Allen provided a tutorial on applying VMM following the Federal Chief Information Officer (CIO) Council's VMM How-To-Guide[13] and facilitated the session using the Analytic Hierarchy Process (AHP) as the decision support method. Expert Choice is a commercial software package that implements AHP and was used by Booz Allen to lead the evaluation and ranking of the weighting factors. The workshop resulted in a set of weights that participants agreed was a valid and balanced score. However, application of the full VMM methodology was rated as being too labor intensive and time consuming for use in quick response studies such as those being conducted by the SCAWG.

As an alternative, Expert Choice was used in an internal SCAWG session to develop relative weights for the FOMs. This resulted in the weights shown in Table 2 which were adequate for SCAWG use although the viewpoint reflected in these weights was limited to communications and system engineers.

5. Cost Analysis

Cost analysis and estimation is a key element of the SCAWG's architecture definition process. Since the SCAWG recommendations are to be used to support budgetary and programmatic decisions including defense of NASA's budget submission to the Office of Management and Budget (OMB), Congress, and the Government Accountability Office (GAO), the SCAWG is working with the NASA Office of the Chief Financial Officer (OCFO) to implement the cost estimation process defined in the forthcoming version of NASA Program and Project Management Processes and Requirements, NPR 7120.5C2. The SCAWG is acting as a test program for the improved cost estimation methodology embodied in this NASA Procedural Requirement (NPR) known as Continuous Cost-Risk Management (CCRM) approach. CCRM is described in detail in the 2004 NASA Cost Estimating Handbook (CEH) (http://www.ceh.nasa.gov).

Cost models are limited to a completeness and accuracy sufficient to discriminate between the various candidate architectures without attempting to capture complete program costs. Cost estimates are not intended to be used for budgetary purposes. Two government-owned cost modeling and analysis tools are being used by SCAWG: the NASA/Air Force Cost Model (NAFCOM) and Automated Cost Estimating Integrated Tools (ACEIT).

The NASA/Air Force Cost Model (NAFCOM) is an automated parametric cost-estimating tool that uses historical space data to predict the development and production costs of new space programs. It uses parametric relationships to estimate subsystem or component level costs for any aerospace hardware including: earth orbital spacecraft, manned spacecraft, launch vehicle, upper stages, liquid rocket engines, scientific instruments, or planetary spacecraft. NAFCOM uses a template selection wizard to configure a default Work Breakdown Structure (WBS) consistent with the type of spacecraft or launch vehicle to be estimated. NAFCOM capabilities include cost risk analysis, stage level trades, a fully integrated version of the Space Operations Cost Model (SOCM), WBS template modification, and data point reporting. SOCM is a multi-level, constructive model that estimates the costs and staffing for space operations projects by a comparison of mission characteristics to an advancing "State of the Practice" (SOP). High-level project characteristics are used to generate a Level 1 estimate with a ± 30% accuracy. Complexity Generators use multivariable equations that employ several cost driving technical and programmatic variables to estimate costs via CERs. The equations are based on the assumption that a project's cost can be explained by the complexity of the project if all cost driving parameters are considered. If the CER were based on all the parameters that impacted the cost, and all the cost drivers for the data points were properly identified, then the CER equation would predict the actual cost.

The primary tool used is ACEIT. At the heart of the ACEIT suite of tools is ACE, the Automated Cost Estimator. ACE can be viewed as an estimating *platform*, in which any kind or level of cost estimate may be built. The user may load a Work Breakdown Structure (WBS) template based on standard programs, or begin from scratch to tailor a specialized WBS. The ACE estimating platform has several layers: WBS, Methodology, Risk, and Sensitivity are the four elements that give the model most of its structure. The WBS segment in ACE allows the user to create as many or as few cost elements as needed. The indenture of the WBS not only signifies the parent-child relation but also determines how costs are summed and allocated.

The Methodology segment of the ACE platform is where CERs are entered and detailed with inputs such as phasing, start/end dates, and appropriation methods. ACEIT comes with several CER libraries. For SCAWG studies, the Unmanned Space vehicle Cost Model (USCM v8) library is used. The CERs within the USCM v8 library are based on satellite data points that include military, NASA, and commercial vehicles. Each CER is created based on a subset of applicable data to produce a relationship with statistically reasonable predictive value. As with the NAFCOM program the user may manually select the satellites that will be used to create a given CER, thus tailoring the CER to the type of satellite that is of interest.

The third important segment of the ACE model is the introduction of Risk. Risk is applied in the model by selecting a distribution that describes how the point estimate may vary and defining the distribution bounds. As an example, one of the risk types is Input Risk, or weight risk. Many of the CERs are driven by weight estimates of the different subsystems, and the uncertainty in the point estimates must be captured. One distribution type is triangular: the point estimate is treated as the peak of the triangle (the most likely value), and the left and right tips of the triangle may be defined with absolute low and high values or as percentages of the point estimate (e.g., giving a range from 90%-150% of the point estimate). When the program is run with Risk "turned on" the results are iterated and random samples for a given weight are generated from the defined distribution.

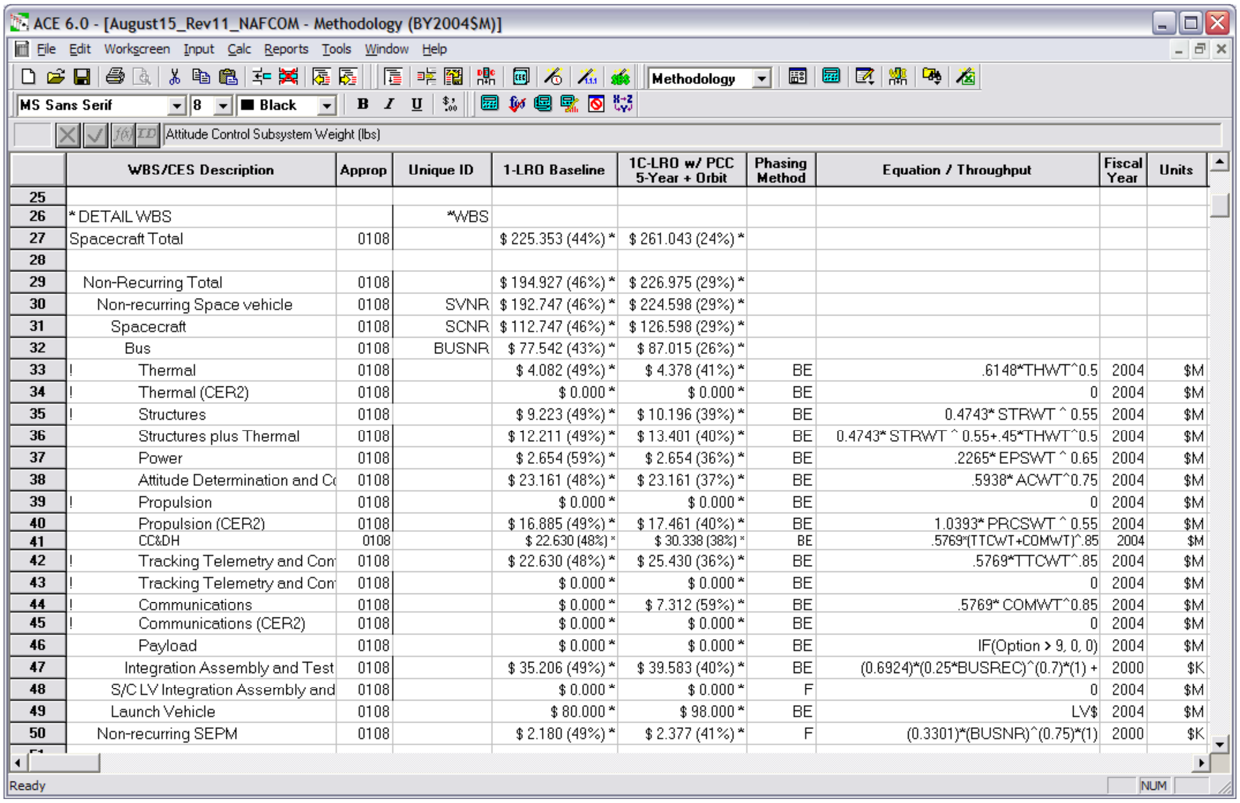
Another feature of the ACE platform is the flexibility to create multiple cases. For each of the design options (including variations of candidate architectures), a separate case was created within each model. The cases can be viewed side-by-side within the Sensitivity segment of the ACE model. Visualizing and reporting a result from multiple cases and two ACE model files is achieved by using the Program Office Support Tool (POST) within ACEIT. POST enables the export of ACE results into Excel. Using POST, reporting and comparing costs at the 70% risk level, as well as combining cost options into solution sets, is a straightforward process. Additionally, each time the ACE sessions are updated, the new results can be exported and the reports in Excel are refreshed using POST.

The end result of using the ACEIT cost platform is an ACE model file, a file that stores ACEIT internal information shared by the ACE and POST tools, and an Excel file generated by POST that captures and compares the results in tabular and graphical form.

For the first SCAWG study, CERs were used from both NAFCOM and the USCM databases to convert estimated spacecraft mass and volume into non-recurring and recurring costs. Differences in cost estimates generated by the two sets of CERs were used to compare and validate the cost models resulting in satisfactory overall agreement. Fig 7 shows a sample of a cost model in ACEIT.

6. Architecture Definition

The body of information constituting the reference SCA, analysis results, and supporting information is currently being maintained on an internal SCAWG web site. The SCAWG plans to transition to the use of Popkin Software's System Architect during Round 2.



	WBS/CES Description	Approp	Unique ID	1-LRO Baseline	1C-LRO w/ PCC 5-Year + Orbit	Phasing Method	Equation / Throughput	Fiscal Year	Units
25									
26	* DETAIL WBS		*WBS						
27	Spacecraft Total	0108		$ 225.353 (44%) *	$ 261.043 (24%) *				
28									
29	Non-Recurring Total	0108		$ 194.927 (46%) *	$ 226.975 (29%) *				
30	Non-recurring Space vehicle	0108	SVNR	$ 192.747 (46%) *	$ 224.598 (29%) *				
31	Spacecraft	0108	SCNR	$ 112.747 (46%) *	$ 126.598 (29%) *				
32	Bus	0108	BUSNR	$ 77.542 (43%) *	$ 87.015 (26%) *				
33	! Thermal	0108		$ 4.082 (49%) *	$ 4.378 (41%) *	BE	.6148*THWT^0.5	2004	$M
34	! Thermal (CER2)	0108		$ 0.000 *	$ 0.000 *	BE	0	2004	$M
35	! Structures	0108		$ 9.223 (49%) *	$ 10.196 (39%) *	BE	0.4743* STRWT ^ 0.55	2004	$M
36	Structures plus Thermal	0108		$ 12.211 (49%) *	$ 13.401 (40%) *	BE	0.4743* STRWT ^ 0.55+.45*THWT^0.5	2004	$M
37	Power	0108		$ 2.654 (59%) *	$ 2.654 (36%) *	BE	.2265* EPSWT ^ 0.65	2004	$M
38	Attitude Determination and Co	0108		$ 23.161 (48%) *	$ 23.161 (37%) *	BE	.5938* ACWT^0.75	2004	$M
39	! Propulsion	0108		$ 0.000 *	$ 0.000 *	BE	0	2004	$M
40	Propulsion (CER2)	0108		$ 16.885 (49%) *	$ 17.461 (40%) *	BE	1.0393* PRCSWT ^ 0.55	2004	$M
41	CC&DH	0108		$ 22.630 (48%) *	$ 30.338 (38%) *	BE	.5769*(TTCWT+COMWT)^.85	2004	$M
42	! Tracking Telemetry and Con	0108		$ 22.630 (48%) *	$ 25.430 (36%) *	BE	.5769*TTCWT^.85	2004	$M
43	! Tracking Telemetry and Con	0108		$ 0.000 *	$ 0.000 *	BE	0	2004	$M
44	! Communications	0108		$ 0.000 *	$ 7.312 (59%) *	BE	.5769* COMWT^0.85	2004	$M
45	! Communications (CER2)	0108		$ 0.000 *	$ 0.000 *	BE	0	2004	$M
46	Payload	0108		$ 0.000 *	$ 0.000 *	BE	IF(Option > 9, 0, 0)	2004	$M
47	Integration Assembly and Test	0108		$ 35.206 (49%) *	$ 39.583 (40%) *	BE	(0.6924)*(0.25*BUSREC)^(0.7)*(1) +	2000	$K
48	S/C LV Integration Assembly and	0108		$ 0.000 *	$ 0.000 *	F	0	2004	$M
49	Launch Vehicle	0108		$ 80.000 *	$ 98.000 *	BE	LV$	2004	$M
50	Non-recurring SEPM	0108		$ 2.180 (49%) *	$ 2.377 (41%) *	F	(0.3301)*(BUSNR)^(0.75)*(1)	2000	$K

Figure 7. Portion of Cost Model Developed in ACEIT (Risk Confidence Levels in Parentheses)

IV. Technology Insertion Plan

There are a wide variety of technology development activities across NASA, the US government, and industry that support advanced communications and navigation capabilities for space applications. This section describes the technology assessment and roadmap development process used by the SCAWG to focus that investment to meet the needs of the exploration initiative. The challenge is to collect, categorize and analyze the various technologies and compare them with the needs of the future communication architecture to develop a technology roadmap for the 2010, 2015, 2020, 2025, 2030 time frames. Since the requirements representing those mission needs have not been established, the SCAWG worked with broad requirements of high data rates and increased connectivity. The assessment identifies key technologies of interest, time required for research & development to mature technologies to TRL 6, and target program niches for insertion of the technologies. This process may serve as the agency's approach to organizing communications and navigation technology research in support all NASA missions.

A. Technology Assessment Process

The assessment process includes a listing of communication elements or areas, identification of system level issues, comparison of state of the art (SOA) with performance requirements, selection of technologies for development or technology transfer-in process, and continued evaluation of these and new technologies as they are identified. A TRL projection is made to determine when these technologies will become available for infusion into the SCA. Development within NASA, other USG agencies, foreign organizations and commercial technology suppliers is included. Fig 8 shows the details of the five step process:

- In Step 1, we identify the system level issues that drive technology needs. Using a taxonomy that lists communication system elements, major concerns for that system element are listed. The relative importance of each concern is placed into a bin or category depending on the severity of the problem. These bins are:
    1. *Mission critical:* Cannot meet even minimum requirement without it.
    2. *Mission important:* Can meet degraded performance requirement.
    3. *Mission optional:* Not needed, but is a performance enhancer; include in trade space.

For example if a spacecraft laser used for an optical communication system does not produce sufficient power, the system will not perform. This is given the highest priority of 1. On the other hand if a well developed technology such as a traveling wave tube does not meet the power level desired, the system can still operate but with degraded performance. In this case the element is assigned a lower priority of 2.

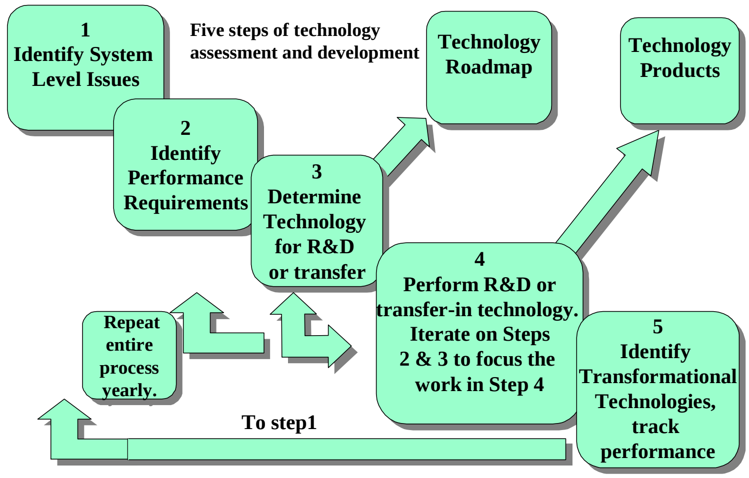


Figure 8. Technology Assessment Process

- In Step 2, we identify performance requirements and compare them with the SOA. This has been a challenging step since performance requirements are based on a lack of defined mission requirements. Also the performance requirement is one required to mitigate the issue. Mitigation is not always easily determined.
- Step 3 determines relevant technology(ies) for investigation, fostering or transfer. It includes the evaluation of TRL and estimated time for completing maturation to TRL 6. At this point the roadmap can be generated.
- In Step 4, we perform the necessary research and development (R&D) to bring the technology to fruition. Sometimes we adapt another organization's technology through a Memorandum Of Understanding or other technology transfer process. An outcome of this step requires that we iterate through Steps 2 and 3 to improve the work in Step 4 by better defining the requirements and deviation from the SOA.
- In Step 5, we identify new transformational technologies as they become identified. The process to identify these transformational technologies is based on the national advanced technology efforts such as those led by the National Science Foundation (NSF) and the Defense Advanced Projects Research Agency (DARPA). It is a result of recommendations of technical experts inside and outside of NASA. Many other government agencies are investing in very low TRL work whose insertion path into communications may not be obvious. In this process we track the development of these transformational technologies for possible inclusion into Step 1 at a later date. If these efforts are successful they could radically transform communications architecture. Quantum entanglement and X-ray Pulsar navigation are examples of such technologies. We are aware of technologies that do not appear to be as closely connected to communications such as nanotechnology and biotechnology, while infotechnology is closely connected to communications.

B. Interaction with NASA Organizations and Other Groups

There are several interactions within the agency that have impacts on this assessment. The Space Architect's Office led the Capabilities Roadmap Analysis and Integration (CRAI) activity in 2004. An outcome was a tabulation and evaluation of several communication technologies. This listing was used early in the technology assessment process to identify the SOA for various elements or areas. Also ESMD took a leadership role in developing preliminary plans that were used as the basis for funding work. The SCAWG requested input and ESMD supplied the requested information for this plan. These plans were considered in developing the SCAWG technology assessment. Also members of the SCAWG participated in the evaluation of proposals submitted in response to the ESMD Request For Proposals. Members of the SCAWG interacted and received information from organizations such as the Department of Defense (DoD). This material has influenced the process as well. Members of the technology assessment team are from various NASA Centers including the Jet Propulsion Laboratory (JPL), Glenn Research Center (GRC), and Goddard Space Flight Center (GSFC) as well as other groups within the technical community.

C. C&N Technology Roadmap Recommendation

At this point, three major recommendations have come from the Technology Assessment Team. The first is a draft set of recommendations (Fig 9). While not inclusive, the technologies on this chart are possible candidates for accelerated development. The technologies are shown in two categories. The transformational technologies are shown above the large horizontal bar entitled "Evolving Comm and Nav Architectures". These are the technologies identified in Step 5. X-ray pulsar navigation would enable precise navigation and pointing of communications system anywhere in the universe, greatly simplifying time transfer. Quantum entanglement would enable secure transfer of information, thereby greatly simplifying the data encryption process. Known as quantum key encryption, any tampering with a transmitted signal would be immediately detected and the information discarded.

Below the horizontal bar are technologies that have an immediate and clear insertion path into utilization and the C&N Technology Roadmap. The technologies listed have high probability of inclusion into the final set of technologies selected for recommendation by the SCAWG. These technologies include software-defined radio; space based range technologies; high performance and advanced antennas; advanced networking technologies; and optical communications for deep space and near earth. Free space optical communications is a developing area with several new technologies required for success as opposed to RF.

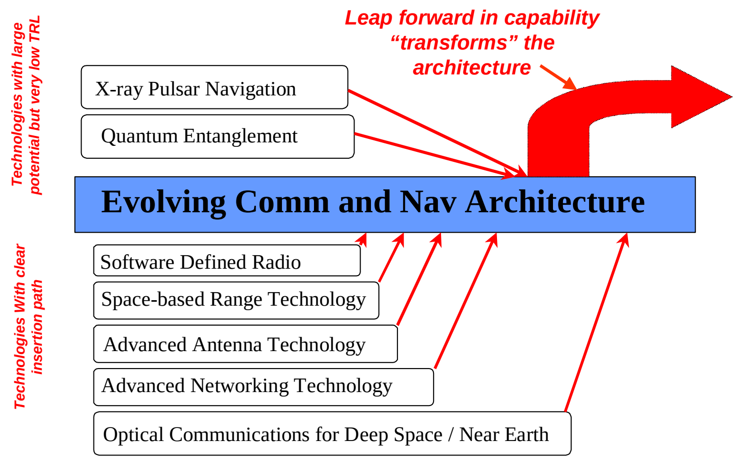


Figure 9. Example Technology Considerations

The Technology Assessment Team's second recommendation is to *continue to support technologies that may be perceived as having matured*. Examples may include high power transmitters for both space to earth and earth to space, spectrum efficiency technologies including bandwidth efficient modulation, coding/decoding, and data compression techniques. These technologies are not listed on the "Example Technology Considerations" chart but technical expertise is required to make certain that NASA will be able to utilize these technologies to their fullest. Possible advancements in space to earth high power amplifiers can be secured if a base level of support is maintained. Also it is desirable to nurture the basic research work, if its importance can be established even if no immediate application is obvious. These two ideas taken together are a recommendation for a continued base research effort in addition to the focused development of technologies listed below the horizontal bar in Fig 9. The Team recommended bridge funding to facilitate the transfer of technology into flight programs allowing a flight program sufficient time to integrate the technology into the management structure.

Finally a third recommendation made by the Technology Assessment Team is that SCAWG review the Roadmap elements at least once per year to update the technologies, determine relevancy as requirements change, and integrate transformational technologies into the development path. The process allows for termination of some activities to make room for other promising activities. This process must also carefully review and scrutinize the higher TRL work for relevance and quality to meet the agency's needs.

D. RF and Optical Communications Systems

RF communications has been the standard in space communications for many years. We clearly understand the technologies that need to be improved to meet the need for increased data rates. High power will be required to support those technologies. However, free space optical communications for space applications is a promising yet challenging area of development. With much larger bandwidth and higher energy beam density than RF communications, laser communications may, under certain conditions, provide higher data rates than RF. For the large distances in the solar system, laser communications can be very beneficial. Compared with RF communications that require large antennas and heavy feed systems, laser communications may be implemented with lower mass and reduced user burden for the same data rates. Studies need to be completed to validate this assertion. While space optical communications is an area with great potential, it is unproven in practice. We can take advantage of the efforts in ground-based optical and other government agency activities but the experience base does not come easily from present space communications capabilities. A lot of research and effort is required to actually bring space based laser communications to operational status.

1. Applications

Free space optical communications is already a reality for terrestrial systems. Commercial products are available for use in local area network (LAN) applications. Space applications such as satellite to ground, or satellite to satellite known as inter-satellite links (ISL) or cross links, have been slower to be developed and are not in common practice. Satellite to ground laser is challenging due to the effect of clouds scattering the laser beam or atmospheric disturbances scattering the laser beam. While laser communications for near earth applications, i.e. ISL or moon-earth relay, may be practical, the impact for deep space (> 2M km) applications is of great interest to NASA. Also ISL for a constellation of satellites around Mars may be very useful for a manned mission. Deep space to earth orbiting assets should be considered for laser communications.

While the details of a particular application depend on many parameters, it appears that the capability (e.g., data rate per kilogram) of the optical systems may be greater than RF-based systems. A laser communications system may have a lower mass requirement for similar data rates compared to RF communications or a higher data rate for similar mass. For example, a planned demonstration of laser communications called the Mars Laser Communications Demonstrator (MLCD), planned to be launched on board the Mars Telecom Orbiter (MTO) in 2009, is designed with an 88 kg flight terminal and planned for about 10 Mbps. Comparable RF systems with similar mass have lower data rates.

The objective of NASA's present effort is to investigate laser communications as a potential agency standard operational communications system for deep space. Applications may include Mars orbiter to earth and to and from the CEV. Other applications may be laser-based ISL between constellation elements around the moon or Mars, from Mars orbiters to earth, Mars orbiters to Earth orbiting assets, or from the outer planets. Some applications do not appear to be candidates for implementation. For example, a Martian surface application may be unlikely. The abrasive Martian dust carried by high velocity winds may be damaging to the optical components. Since the data rates required for surface LANs are expected to be less than 100 Mbps, drivers for such an implementation do not seem to be present.

2. Technical Challenges

Several key technical challenges are associated with development and implementation of space based laser communications. Areas of research include sensitive detectors, efficient sources for lasers and optical amplifiers, and optomechanical devices. The optomechanical devices for pointing systems and beamsteering need to work in a high vibration environment maintaining directionality without excessive jitter at distances from Mars and beyond (> 400M km). Detectors that have sufficient sensitivity for the weak optical radiation from deep space are being developed. NASA has a portfolio of technologies in development to extend laser communications to the outer planets. Acquisition of the beam is difficult without the nearly instantaneous beacon feedback from the receiver as is possible for near earth laser communication.

3. RF and Optical Communication Conclusions

NASA has had an interest in optical communications for space application for many years as demonstrated by a NASA conference on this topic as early as 1968.[14] The present approach of flight projects and supporting research for continual product improvements and application to deeper space is the right one. Particular emphasis needs to be placed on the detectors, sources and optomechanical devices for pointing control since all of these will be greater issues for the outer planets. Concern exists regarding MLCD's use of a wavelength that is not standard preventing NASA from taking advantage of developments by commercial and other organizations. This topic deserves further consideration.

Finally we would not expect to quickly replace RF communications with laser communications. Mission managers see the "tried and true" capabilities as more reliable than newer technologies. Furthermore, Ka-band RF may be able to provide the data rates required with larger antennas, more powerful transmitters and larger earth receive terminals. Larger inflatable antennas with ten times the diameter (100 times the area) and 10 times more powerful amplifiers may make RF data rates of gigabits per second possible. Therefore, the SCAWG is performing an assessment of RF and optical systems to determine the relative strengths, near and far term potential applications, and costs for implementation.

E. Technology Request For Information

The SCAWG released a Request For Information (RFI)[15] in July 2004 for the purpose of collecting information relevant to planning NASA's future Space Communications Architecture. Exploration and science initiatives will require robust, extensible communications. The broad perspective from industry and academia is invaluable in assisting the SCAWG in planning the future space architecture. Almost twenty organizations, including two universities, responded to the RFI. The responses were evenly divided between small and large companies. Some supplied white papers for our consideration but did not offer to present. Other submitters, based on their white papers, desired to give an oral presentation and are being invited to present at SCAWG meetings. The input represented a number of technologies including component technologies, systems and subsystems, and networking concepts.

In August the RFI[16] was amended to request information relevant to planning NASA's ground network for the future SCA. NASA is seeking information on cost estimates for services related to ground stations to perform the following functions: TT&C of lunar orbiters with 24/7 coverage and TT&C of government earth orbiters with 24/7 for Launch Early Orbit and Anomaly (LEO&A) coverage. The TT&C will operate using Unified S-Band (USB). Cost and reliability estimates were received by 15 September. The response from industry helped focus NASA plans.

The RFI will continue to be active in 2005 and the SCAWG is still accepting white papers and inviting presentations. Check the NASA Acquisition Internet Services (NAIS) website (http://prod.nais.nasa.gov/cgi-bin/nais/index.cgi) as additional amendment postings may follow.

V. Top Level Solar System Space Communication Architecture

A. Philosophy of the Space Communications Architecture

The SCA is being developed in the context of meeting all of NASA's space communication needs through a communication system of systems that evolves from today's architecture to support for missions that are part of campaigns spanning a decade or more. This operates within the greater context for the 21st century of a Science Vision to understand life and the universe and an Exploration Vision to expand human presence across the solar system. Architecting a system of systems that spans the solar system and beyond over the course of decades requires that we adopt a philosophy for the long view that allows planned evolution and incorporation of new technologies while accommodating constant ongoing changes from year to year. Key tenets of our approach can be summarized in the following heuristic rules:

- Maintain consistency with spectrum allocations defined by the International Telecommunication Union (ITU) and NASA policy.[3-4]
- Everything that is launched is an element of the architecture connected to the Earth.
- Everything that is launched is a potential node for relaying data between other nodes.
- Use communication packages on spacecraft in situations with low to medium data rates or extremely long distances (greater than Mars).
- Transition from communication packages to dedicated relay satellites providing trunk (typically backhaul) links when the data traffic reaches a threshold where it becomes cheaper or more effective for mission support to deploy dedicated infrastructure.

The result of applying these rules is the SCAWG's top level SCA for the solar system (Fig 10). The SCA portrayed here is the working reference of the SCAWG and includes systems regardless of their funding status.

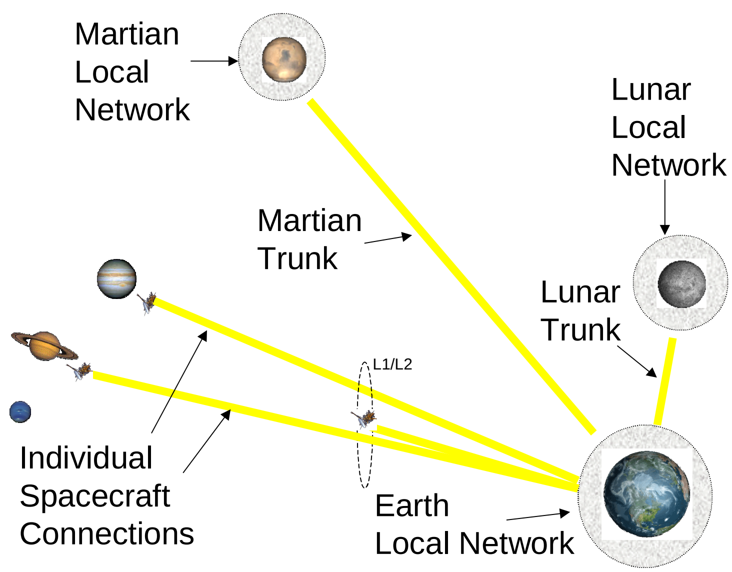


Figure 10. Top Level Solar System Space Communication Architecture

B. Spectrum

Spectrum selection and utilization for lunar and deep space operations are based on the protection afforded by spectrum allocation though the ITU and the government entities in countries where NASA operations take place as well as a technical assessment of the possibility of interference to and from other services sharing these allocations. The Moon has a special radio quiet zone defined in the ITU radio regulations, called the Shielded Zone of the Moon (SZM), located on the back side of the Moon and extending in a cone above the Moon's surface that is allocated to support radio astronomy use. The ITU radio regulations allow transmissions to occur when operating in Space Research Service (SRS) allocations in the SZM limited to the 2 to 3 GHz region[**]. Frequency ranges have been allocated by the ITU for use in deep space and near-Earth research (Table 3).

Table 3. ITU Allocated Frequency Bands

Band Designation	Deep Space Bands (for spacecraft greater than 2 million km from Earth)		Near Earth Bands (for spacecraft less than 2 million km from Earth)	
	Uplink (Earth to space)	Downlink (space to Earth)	Uplink (Earth to space)	Downlink (space to Earth)
S-band	2110–2120	2290–2300	2025–2110	2200–2290
X-band	7145–7190	8400–8450	7190–7235	8450–8500
Ka-band	34200–34700	31800–32300		

Tables 4 and 5 list the ITU worldwide S- and X-band frequency allocations and services, respectively. They also identify the allocations for the NASA Deep Space Network (DSN) in the 2110 - 2120 MHz, 2290 – 2300 MHz, and 8400 – 8500 MHz bands. GN stations must control unwanted emissions in these DSN bands.

NASA coordinates recommendations on use of the electromagnetic (EM) spectrum through the Space Frequency Coordination Group (SFCG) and participation with the Federal Communication Commission (FCC), Department of State, and the National Telecommunication and Information Administration’s (NTIA) Interdepartment Radio Advisory Committee (IRAC).

Table 4. S-Band International Frequency Allocations

Frequency (MHz)	Service Allocation
2025 – 2110	SPACE OPERATION (earth-to-space and space-to-space) EARTH EXPLORATION-SATELLITE (earth-to-space and space-to-space) FIXED MOBILE SPACE RESEARCH (earth-to-space and space-to-space)
2110 – 2120	FIXED MOBILE SPACE RESEARCH (DSN) (earth-to-space)
2200 – 2290	SPACE OPERATION (space-to-earth and space-to-space) EARTH EXPLORATION-SATELLITE (space-to-earth and space-to-space) FIXED MOBILE SPACE RESEARCH (space-to-earth and space-to-space)
2290 – 2300	FIXED MOBILE

C. Earth Network (EN)

The EN consists of the set of orbiting and ground systems that collectively provide tracking, data relay, telecommunications, and related support services to all NASA users including Exploration, Science, and Operations missions. In the 2005 through 2015 time frame, the EN is composed of four systems: Space Network, Deep Space Network, Ground Network, and NASA Integrated Services Network.

1. Space Network

The SN consists of two primary elements: the White Sands Complex (WSC) and a fleet of Tracking and Data Relay Satellites (TDRS) in geosynchronous orbit.

The WSC consists of three facilities. The two large facilities are known as the White Sands Ground Terminal (WSGT) and the Second TDRS Ground Terminal (STGT) and are located just outside Las Cruces, NM (and are separated by approximately six miles). The third ground terminal in the SN is the Guam Remote Ground Terminal

[**] The International Astronomical Union (IAU) plans to identify an additional 1 GHz band for lunar communication systems in the SZM.

Table 5. ***X-Band International Frequency Allocations***

Frequency (MHz)	Service Allocation
7075 – 7250	FIXED MOBILE
8025 – 8175	EARTH EXPLORATION-SATELLITE (space-to-earth) FIXED FIXED-SATELLITE (earth-to-space) MOBILE
8175 – 8215	EARTH EXPLORATION-SATELLITE (space-to-earth) FIXED FIXED-SATELLITE (earth-to-space) METEOROLOGICAL-SATELLITE (earth-to-space) MOBILE
8215 – 8400	EARTH EXPLORATION-SATELLITE (space-to-earth) FIXED FIXED-SATELLITE (earth-to-space) MOBILE
8400 – 8500	FIXED MOBILE SPACE RESEARCH (DSN) (space-to-earth)

(GRGT). These three ground terminals allow the SN to offer complete global coverage for customers. These facilities are staffed 24x7 to provide services to the SN user community in addition to being the control center for the TDRS constellation.

The fleet of spacecraft is situated in Earth orbit such that they can provide continual, global coverage. In 2005, there are nine spacecraft in orbit, five of which are being used daily to support the low Earth customer community. Of these five spacecraft, two are located just off the coast of South America over the Atlantic Ocean, two are over the middle of the Pacific Ocean, and one over the Indian Ocean. There is one satellite that is solely used to support National Science Foundation (NSF) operations at the South Pole and is not available for service to other customers. The other spacecraft are stored on-orbit as spares for the operational fleet. In 2010, this constellation remains in operation subject to potential failures due to the aging fleet (Fig. 11). By 2015, two new TDRS satellites, F-K and F-L, are added to replenish the constellation maintaining the same system capacity and 99% user satisfaction service level.

This projection is based on several assumptions. EOS science functions are transitioned to the National Oceanic and Atmospheric Administration (NOAA) via the National Polar-orbiting Environmental Satellite System (NPOESS). ISS continues in operation but the Shuttle is retired. ISS is attended once per month by a combination of Ariane Transfer Vehicles (ATV), H-II Transfer Vehicles (HTV), and Commercial Visiting Vehicles (CVV). Support is provided to the SMall EXplorer (SMEX), Medium-class Explorer (MIDEX), and Earth System Science Pathfinder (ESSP) programs. CEV includes Earth orbit rendezvous operations. Two-thirds of the currently approved missions survive into the 2015 period. Launch & Early Operations (LEOP) support is provided for Robotic Lunar Exploration Program (RLEP) missions.

There are several services provided by the SN including telecommunications, tracking and clock calibration, testing, and analysis (Table 6). Table 7 shows which services are used by spacecraft in 2010.

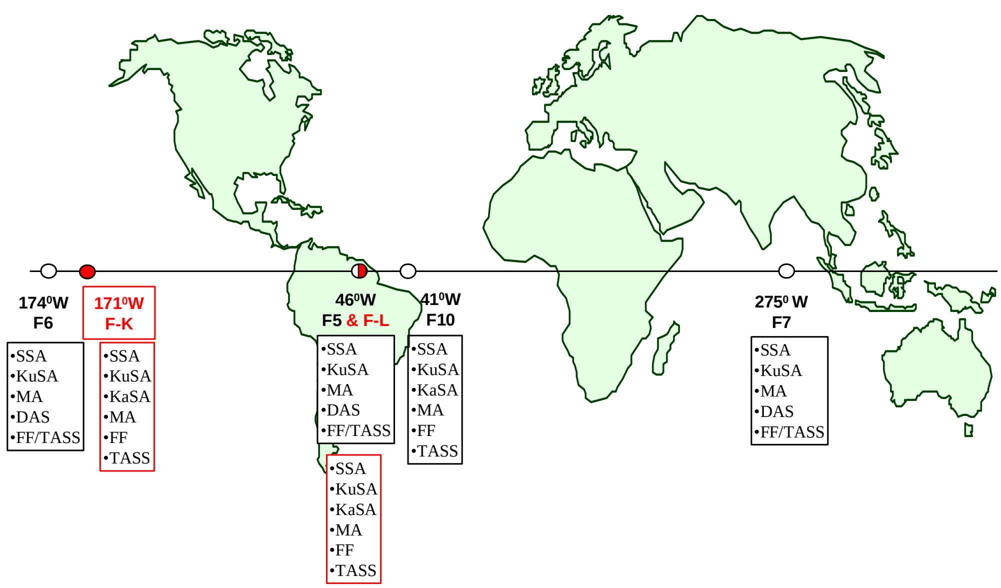


Figure 11. SN Architecture for 2010 (white nodes) & 2015 (red Replenishment TDRS Satellites)

Table 6. SN 2010 Capabilities

Service			TDRS 1-7	TDRS 8-10	Notes
Single Access	S-band	FWD	7 Mbps	7 Mbps	No Change
		RTN	6 Mbps	6 Mbps	
	Ku-band	FWD	25 Mbps	25 Mbps	
		RTN	300 Mbps	300 Mbps	
	Ka-band	FWD	N/A	25 Mbps	>300 Mbps available via IF service
		RTN	N/A	300 Mbps/up to 1.2 Gbps*	
	Number of Links per Spacecraft		SSA: 2/TDRS; 10/WSC; 2/GRGT KuSA: 2/TDRS; 10 KuSA/WSC; 2/GRGT	SSA: 2/TDRS; 10/WSC; 2/GRGT KuSA: 2/TDRS; 10 KuSA/WSC; 2/GRGT KaSA: 2/TDRS; 8/WSC;	For TDRS H, I, J simultaneous operation of S & Ku and S & Ka services via a single SA antenna are required
Multiple Access	Number of Links per S/C	FWD	1/TDRS @ up to 300 kbps; 4/WSC; 1/GRGT	1/TDRS @ up to 300 kbps; 4/WSC (8 dB over TDRSS)	Anticipated SSA users < 3 Mbps off-loaded to TDRS H, I, J MA
		RTN	5/TDRS @ up to 300 kbps; 20/WSC; 2/GRGT	5/TDRS @ up to 3 Mbps; 20/WSC	
Customer Tracking			150 meters 3 sigma	150 meters 3 sigma	No Change

Table 7. SN Service Types in 2010

Potential 2015 Customers	*Mission*	*Payload*	*TT&C*	*MA*	*SA*	*DAS*	*TASS*	*FastForward*
ATV	H	?	?	?	S			
Balloons	S	?	?			?	?	?
Commercial Visiting Vehicles	R	?	?		S		?	
ELVs	Various		?		S			
ESSP Series	S	?	?		S,Ku		?	?
GLAST	S	?	?		Ku	?		?
GLORY	E	?	?		S		?	?
GPM Core	E		?			?	?	
HTV	H	?	?	?	S			
HYDROS	E	?	?		S		?	?
ISS	H	?	?		S,Ku		?	
JEM	H	?			Ka			
LEOP	Various		?		S			
MIDEX Series	S	?	?		S,Ku		?	?
NPOESS-1	E		?	?			?	?
NPOESS-2	E		?			?	?	?
NPOESS-3	E		?			?	?	?
NPP	E	?	?		S			
ODSI	USAF	?	?		S,K		?	
RLEP	S	?	?		S,Ka		?	
CEV	X	?	?		S,Ka		?	
SmallSat Series	S	?	?		S		?	?
SMEX Series	S	?	?		S		?	?
Solar Physics Missions	S	?	?		S		?	?
South Pole	NSF	?			S,Ku			
University Missions	E,S	?	?		S,Ku	?	?	?
WISE	S	?	?		S,Ku		?	

GLAST	Gamma Ray Large Area Space Telescope	Missions:	
GLORY	Global Observatory for aerosols and solar irradiance	E	External
GPM	Global Precipitation Measurement	H	Human Spaceflight
HYDROS	Hydrosphere State	NSF	National Science Foundation
JEM	Japanese Experiment Module (part of ISS)	R	Commercial
NPP	NPOESS Preparatory Project	S	Science
ODSI	Orbital Deep Space Imager	USAF	US Air Force
WISE	Wide-Field Infrared Survey Explorer	X	Exploration

Telecommunications: This is the service that operates either via the Multiple Access (MA) or Single Access (SA) antenna systems on the TDRS. The MA system operates in the S-band frequency. The SA system operates in the S-band, Ku-band or Ka-band frequencies. Ka-band is only available on the TDRS H, I, J, K, L, M series of spacecraft. These services are generally scheduled in advance by the customer control center. The schedule will be based on when their spacecraft is in view of a TDRS and when they need to communicate with their spacecraft. Users can access to the MA system on demand (without prior scheduling) through Demand Access Service (DAS) return service and FastForward forward service. This addresses the needs for “911” alerts, science event alerts, sensor webs, continuous data streams, flexible mission support (unscheduled/event driven), and simplified mission operations with end-to-end Internet Protocol (IP) services. DAS provides data rates from 1-150 kbps/channel.

Higher data-rate missions requiring High Definition TV (HDTV) and extreme precision instruments utilize the increased K-band capability in 2015 on TDRS F-K / F-L through the TDRS K-band UPgrade (TKUP). Mission critical Events needing real time telemetry and command during LEOP, orbit maneuvers, and EVA are met by improved fleet management for global coverage and direct GN connectivity through SN. Interoperability to support non-NASA missions is provided through service during LEOP, critical events, and emergency support via the Consultative Committee for Space Data Systems (CCSDS) Space Link Extension (SLE) data transfer services and end-to-end IP services.

Tracking and Clock Calibration: This service provides the customer with the ability to understand their precise location in orbit using Doppler measurements. It also allows them to determine the accuracy of their onboard clock (and to make updates if necessary). Emerging needs for autonomous rendezvous and docking, formation flying, on-board navigation, and higher precision instruments are met by adding the TDRSS Augmentation Service for Satellites (TASS) which combines TDRS and GPS data to provide higher precision tracking.

Testing: The SN provides two types of testing services: compatibility testing and end-to-end testing. Compatibility testing is done to ensure that the communications package on the customer spacecraft is compatible with the communications system of the SN. This testing is performed while the customer spacecraft is in development. End-to-end testing is performed at various points of the customer spacecraft lifetime. This testing can be performed using a ground-based simulator for the customer spacecraft. End-to-end testing performed prior to launch helps ensure the full operational capability of the customer system including operations and fault isolation procedures. End-to-end testing is also performed once the customer spacecraft has been launched to validate that changes made to either the customer systems or the SN will not cause problems in operations.

Analysis: Communications link analysis enables the customer to understand what the parameters of their communication system need to be in order to be able to communicate (or close the link) with the TDRS. Link analysis also examines the impact of locating the customer spacecraft antenna at various places on their spacecraft and what this would do the communications link between them and the TDRS. This analysis is done during the design and development of the customer spacecraft communication system.

Mission demand in 2015 is projected to require 7 to 9 SA to cover peak loads and 6 SA to guarantee “steady-state” requirements. At least 2 SA are required at each node for rendezvous operations and “co-incident” support. MA/DAS service is required globally for missions that require “911” or science event alerts. Peak loads occur for launches, LEOP support, and rendezvous operations (including CEV). Other services implemented by 2010 include:

- The Space Network Expansion (SNE) provides a dedicated capability to meet specific customer needs quickly using TDRS H,I, J. The ground terminal (SNE-West) is at Guam but can be remotely operated from the WSC. The SNE provides GN Mode Services (USB) via the TDRS SA antennas; non-coherent modulation and data rates for Ku- and S-Bands; forward Doppler compensation; and baseband and Intermediate Frequency (IF) interfaces to accommodate unique customer equipment.
- The Space Network Access System (SNAS) is the primary scheduling interface between the SN customer and the SN. SNAS provides a network-based (server-client relationship) customer interface for performing SN scheduling and real-time control and monitoring. It supports customers who currently schedule SN services through both the Network Control Center Data System (NCCDS) and the Demand Access System (DAS). It is accessible from the Internet and the NISN Open and Closed IONet and provides for easy system setup and workstation independence for the SN customer as the SNAS client software runs on any type of personal computer or workstation.

2. Deep Space Network

The DSN consists of ground terminals at locations in Spain, Australia, and California that are approximately 120 degrees apart in longitude, which enables continuous observation and suitable overlap for transferring the spacecraft (Fig. 12). Each complex consists of at least four deep space stations equipped with ultra-sensitive receiving systems and large parabolic dish antennas. There are:

- One 34-meter (111-foot) diameter High Efficiency (HEF) antenna
- One 34-meter Beam Waveguide (BWG) antenna (Three at the Goldstone Complex)

- One array of four 12-meter (39-foot) antennas
- One 70-meter (230-foot) antenna

The ability to array several antennas improves the data returned from outer planet and deep space spacecraft. The array electronically links the 70-meter antenna at the DSN complex in Goldstone with an identical antenna located in Australia, in addition to two 34-meter (111-foot) antennas at the Canberra complex. All the stations are remotely operated from a centralized Signal Processing Center (SPC) at each complex. The Centers house the electronic subsystems that point and control the antennas, receive and process the telemetry data, transmit commands, and generate the spacecraft navigation data. Once the data is processed at the complexes, it is transmitted to JPL for further processing and distribution to science teams over a modern ground communications network.

The DSN 70-m Antenna Subnet contains three 70-meter diameter antennas. One antenna, Deep Space Station (DSS) 14, is located at Goldstone, California; one (DSS 43) is near Canberra, Australia; and one (DSS 63) is near Madrid, Spain. All antennas support L-, S-, and X-band reception, and S-band and X-band transmission. The Goldstone site also has an X-band radar transmitter (Goldstone Solar System Radar, GSSR) in a third cone that operates near the normal receive frequency band. In this third cone is also a Ku-band (22 GHz) receive feed for radio astronomy investigations.

The DSN 34-m Antenna Subnet contains three 34-meter diameter HEF antennas. One antenna (DSS 15) is located at Goldstone, California; one (DSS 45) near Canberra, Australia; and one (DSS 65) near Madrid, Spain. In addition to spacecraft tracking, the DSN 34-m Antenna Subnet is also used for very-long baseline interferometry and

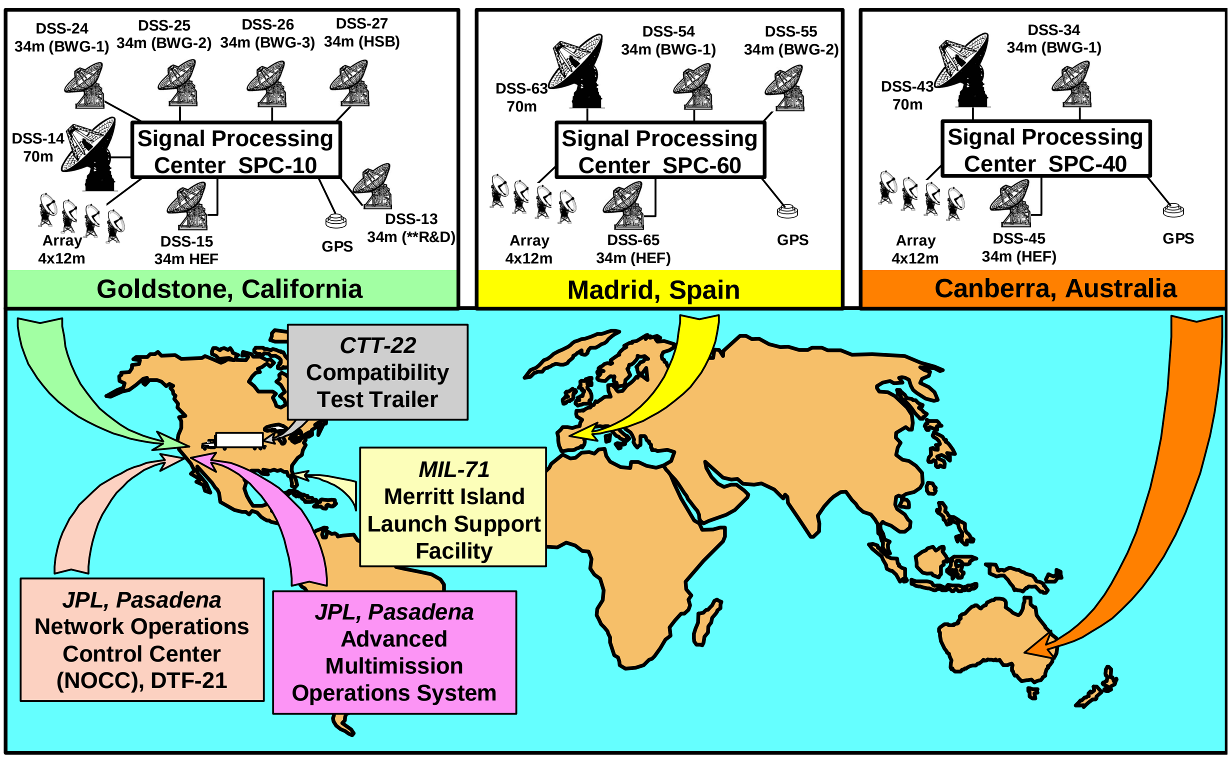


Figure 12. Deep Space Network Architecture in 2010

radio-source catalog maintenance.

The 34-meter diameter BWG (beam waveguide) and HSB (high angular-tracking speed beam waveguide) antennas are the latest generation of antennas built for use in the DSN. These antennas differ from more conventional antennas in the fact that a series of small mirrors, approximately 2.5 meters in diameter, direct microwave energy from the region above the main reflector to a location in a pedestal room at the base of the antenna. The pedestal room is located below the azimuth track of the antenna and, with the exception of the HSB antenna, below ground level. In this configuration, several "positions" of microwave equipment, contained in the pedestal room, can be accessed by rotation of an ellipsoidal mirror located in the center of the pedestal room floor beneath the azimuth axis of the antenna. This enables great versatility of design and allows tracking with equipment at one position while equipment installation or maintenance is carried out at the other positions. Since cryogenic low-noise amplifiers (LNAs) do not tip as they do when located above the elevation axis, certain state-of-the-art, ultra low noise amplifier (ULNA) and feed designs can be implemented. The HSB antenna differs from the BWG antennas in that the pedestal room is above ground level, the microwave optics design is different, and the subreflector does not focus automatically for the purpose of maintaining gain as the elevation angle of the antenna changes. The HSB antenna has higher tracking rates than do the BWG antennas and is equipped primarily for tracking Earth-orbiting satellites.

The major change in the DSN from 2005 is the retirement of the 26m subnet and installation of the beginnings of an array of 12m antennas at each site. The predicted growth in deep space mission downlink requirements from 2005 to 2030 is on the order of 10^6 in combined data rate and link difficulty (Fig 13). To meet this extraordinary growth a variety of measures and new technologies will be necessary to meet forecasted demands (Fig. 14).

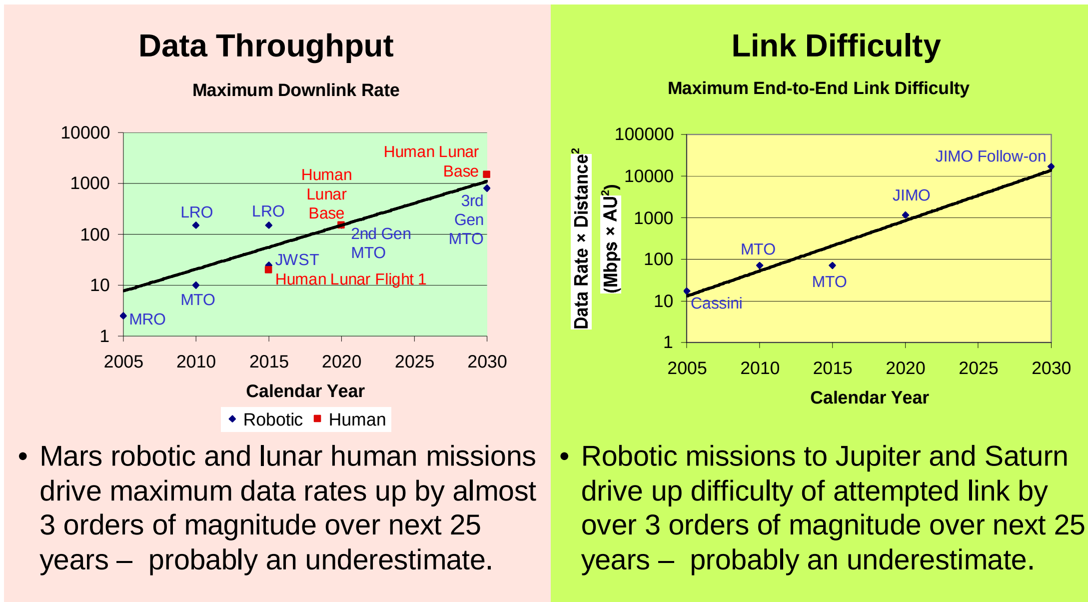


Figure 13. Projected Growth in DSN Downlink Requirements and Proposed Solutions

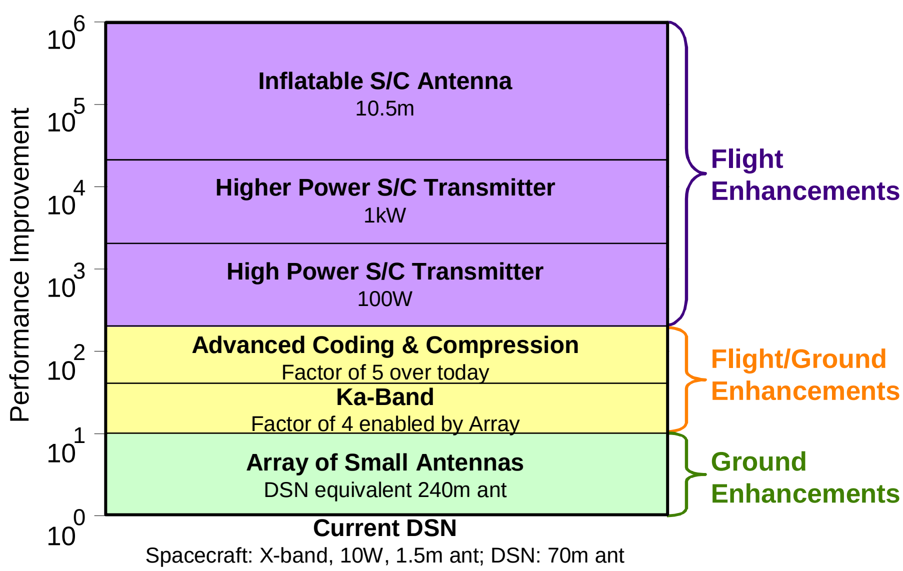


Figure 14. Projected Growth in DSN Downlink Requirements and Proposed Solutions

Today's architecture using large antennas is not sufficient to meet the needs of NASA's future mission set (sensitivity and navigation) and is expensive to maintain and operate. A new approach is to use arrays of small antennas that are reliable, cost effective, and scalable growth in to meet growth in demand. Our trade study concluded that 12m antennas are commercially available at reasonable cost, provide graceful degradation in performance in case of antenna or receiver failures with no single points of failure, and meet the science data rate requirements projected by SMD for most future missions. The array concept accommodates significant growth in the number of spacecraft since it could service several missions simultaneously, each with just the required aperture. Furthermore, these antennas have significant commercial support and have longer lifetimes than the large antennas. The 12m array is designed to grow at least up to 400 antennas which would provide an aperture equal to a 240m antenna or 120 times the capability of our current 70m antenna at X-band. Subarrays provide optimal aperture size for each of several spacecraft. Multiple spacecraft in various parts of the sky or up to 16 spacecraft close together in the sky can use utilize full sensitivity of the array.

The initial array consists of four 12m antennas at each DSN site to support the RLEP missions beginning in late 2008. The arrays grow over time to meet demand following the "Pay as you go" philosophy reaching the full planned size of 400 antennas by 2020.

3. Ground Network

The GN consists of NASA ground stations located in Norway, Florida, Alaska, Antarctica, and the Wallops Flight Facility (WFF) in Virginia with capabilities as shown in Table 8.[17] The GN also includes support from the Network Integration Center (NIC) located at GSFC and the Data Services Management Center and VHF systems at the White Sands Complex (WSC), New Mexico.

Table 8. GN 2010 Assets and Capabilities

Station	Antenna Diameter	Transmit Frequency (MHz)	EIRP (dBW)	Receive Frequency (MHz)	G/T (dB/K)	Location	User Tracking
SGS–NASA (Norway) KSAT Owned KSAT Owned	11.3 m 11.3 m 13 m	2025-2120	66 64 68	2200-2400 8000-9000	23/35.4 22.6/35.4 23/36	78°N 15ºE	1- & 2-Way Dop, Angle
11.3-m System (WFF)	11.3 m	2025-2120	66	2200-2400 8000-9000	23 35	38°N 75°W	1- & 2-Way Dop, Angle
LEO-T (WFF)	5 m	2025-2120	59	2200-2300	17	38°N 75°W	—
TOTS (WFF)	8 m	2025-2120	62	2200-2400	21	38°N 75°W	1- & 2-Way Dop, Angle
9-m System (WFF)	9 m	2025-2120	66	2200-2300	24	38°N 75°W	1- & 2-Way Dop, Range, (Angle TBD)
MGS (Antarctica)	10 m	2025-2120	63	2200-2400 8025-8400	21.1 32.5	78°S 193°W	—
LEO-T (Alaska)	5 m	2025-2120	59.2	2200-2300	17	65°N 147°W	—
TOTS (Alaska)	8 m	2025-2120	62	2200-2400	21	65°N 147°W	1- & 2-Way Dop, Angle
AGS - NASA (Alaska) DataLynx Owned	11.3 m	2025-2120	66 64.5	2200-2400 8000-9000	23 36 / 34.5	65°N 147°W	1- & 2-Way Dop, Angle
ASF (Alaska)	10 m 11.3 m	N/A	N/A	2200-2400 8000-9000	21.1 / 23 32.5 / 35	65°N 148°W	—
MILA (Florida)	9 m (2)	2025-2120	63	2200-2300	24	29°N 81°W	1- & 2-Way Dop, Range, Angle
PDL (Florida)	4.3 m	2025-2120	58	2200-2300	11	29°N 81°W	—

AGS – Alaska Ground Station; ASF – Alaska SAR Facility; LEO-T – Low Earth Orbiter-Terminal; KSAT – K-band SA Terminal; MGS – McMurdo Ground Station; MILA – Merritt Island Launch Area; PDL – Ponce De Leon; TOTS – Transportable Orbital Tracking System; SGS – Svalbard Ground Station; WFF – Wallops Flight Facility

The Earth Observing System (EOS) Polar Ground Stations (EPGS) project consists of two high latitude multi-mission ground stations. The Alaska Ground Station (AGS) is located at the Poker Flat Research Range near Fairbanks, Alaska. The Svalbard Ground Station (SGS) is located in Norway on Spitsbergen, the main island in the Svalbard archipelago. Each station supports S-band command and telemetry and X-band telemetry. Both EPGS stations have automated components, and are scheduled and monitored from the Data Services Management Center (DSMC) at the White Sands Complex.

The primary orbital assets at WFF consist of the 11.3 meter system, Low Earth Orbiter-Terminal (LEO-T), Transportable Orbital Tracking System (TOTS), and the 9 meter system. Wallops Orbital Tracking Information

System (WOTIS) performs scheduling for all these systems. WOTIS is the GN scheduling system, which is located at the DSMC at the White Sands Complex near Las Cruces, NM. Using either automated or manual processes, all orbital apertures are scheduled through the WOTIS

McMurdo Ground Station (MGS) is located at McMurdo Station in Antarctica. It supports S-band command and telemetry and X-band telemetry. WOTIS provides automated scheduling. In addition to the AGS discussed above, the Poker Flat Research Range contains two other ground stations: Low Earth Orbiter-Terminal (LEO-T) and Transportable Orbital Tracking System (TOTS). The LEO-T and TOTS stations in Alaska support S-band command and telemetry. These stations are located 30 miles northeast of Fairbanks.

There are two GN stations in Florida: Merritt Island Launch Area (MILA) and Ponce De Leon (PDL). They primarily support Space Shuttle launches and landings. MILA and PDL support S-band command and telemetry. The DSMC, located at the White Sands Complex in New Mexico, schedules both stations.

The White Sands Complex (WSC) VHF Air/Ground (A/G) Ground Stations are located near Las Cruces, New Mexico. They are used only to support the International Space Station and Soyuz spacecraft. The VHF-1 system can transmit and receive voice and support packet data on the uplink. The VHF-2 system supports only voice.

The baseband data interface and storage equipment options at the GN stations include these services: NISN IP Network, Serial Clock and Data, 4800-Bit Block Encapsulated in IP Packets, Mail Delivery of Recorded Data, and Standard Autonomous File Server (SAFS). For those GN stations that support it, the NISN IP Network can be used by MOCs to send commands to and receive telemetry data from a GN station. The NISN IP Network uses both open and closed NASA IP networks. The NISN IP Network supports both Transmission Control Protocol/Internet Protocol (TCP/IP) and User Datagram Protocol/Internet Protocol (UDP/IP).

4. *NASA Integrated Services Network*

This paper does not address the NISN architecture.

D. Moon

1. *LN 2010*

The LN in the 2010 time frame is designed to support the RLEP. Starting in 2008, NASA will initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities. The primary purpose of the robotic preparation and support for human missions is to reduce risk, enhance mission success, and reduce cost of future human missions. This will be accomplished by designing and implementing a lunar program of robotic missions to collect critical measurements, demonstrate key technologies and emplace essential infrastructure. The first RLEP mission is the Lunar Reconnaissance Orbiter (LRO) planned for a 2008 launch (Fig. 15). Subsequent RLEP missions will include lunar landers probing for detailed understanding at specific South Pole locations that will not have Line Of Sight (LOS) view of the Earth, consequently requiring data relay from the surface to Earth. The primary mission of the LRO is a one-year science mission to map lunar geodetic topography, characterize the lunar radiation environment, and prospect for useful resources such as water, focusing on the South Pole. Subsequent RLEP missions were not defined in detail at the time of the SCAWG study. Hence, we determined the anticipated worst case data requirements over the RLEP series in coordination with the RLEP Program Office and ESMD.

The reference communication architecture for the RLEP program is to integrate a Proximity Communication Capability (PCC) into the LRO and second RLEP mission spacecraft. The LRO performs its primary science mission during its first year in a 50 km polar circular orbit before boosting to a higher polar circular orbit to perform its secondary data relay mission for at least one year. The LRO's PCC receives data from subsequent RLEP lunar landers located in the south polar region from 80-90° S latitude and returns the data directly to Earth. The preliminary requirements identified for the PCC are:

a. The maximum data rate is 1 Mbps return link to support "internet video", Mars Exploration Rover (MER) quality imagery, lower data rate instruments, and Telemetry, Tracking and Control (TT&C).
b. The high end of all identified needs was considered and was consistent with a low power S-band package.
c. The minimum elevation angle for lunar landers to view the relay satellite is 10º providing adequate data volume at low altitude (>480 Mb/pass at 100 km relay altitude at 90ºS). The limb of the moon location (80º S latitude) would limit data volume per pass.
d. No requirement for real-time robotic control (latency) was identified.
e. The RLEP lunar lander multiplexes data streams from various science instruments and transmits one return channel to the orbiting PCC relay.

- Mission is "Discovery Class" in Scope
- One year primary mission in ~50 km polar orbit, possible extended mission in 30x216 km relay/south pole observing orbit
- LRO Total Mass ~ 1000 kg/400 W
- Launched on Delta II Expendable Launch Vehicle (ELV)
- 100 kg/100W payload capacity (3 to 6 six instruments of varying complexity)
- 3-axis stabilized pointed platform (~ 60 arc-sec or better pointing)
- Articulated solar arrays and Li-Ion battery
- Spacecraft to provide thermal control services to payload elements if required
- Ka-band high rate downlink (100-300 Mbps, 900 Gb/day), S-band up/down low rate
- Centralized Mission Ops Center operates mission and flows level 0 data to Principal Investigators (PI), PI delivers high level data to Payload Data System
- Command & Data Handling: MIL-STD-1553, RS 422, & High Speed Serial Service,
- PowerPC Architecture, 200-400 Gb Solid State Recorder,
- Consultative Committee on Space Data Systems (CCSDS) standard protocols
- Mono or bi-prop propulsion (500-700 kg fuel)

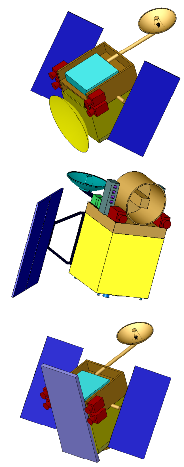


Figure 15. LRO Concept and Mission Design

The third and fourth RLEP missions may also require PCC packages depending on mission launch dates, duration, and landing location. However, the RLEP requirements were too uncertain at the time of the study to make this a requirement.

2. LN 2015

By the 2015-2020 time frame, missions are sending humans to the Moon and establishing a limited infrastructure as we explore the lunar surface for resources and experiment with In Situ Resource Utilization (ISRU). The short-lived RLEP missions have been deactivated after achieving their design lifetimes and relaying the science data that has resulted in a more accurate lunar gravity model for navigation and accurate terrain maps including the dark corners of craters that have never seen Sun or Earth shine. Spectrum usage remains consistent with international agreements and NASA policy.[3-4] The set of services required and the users of these services shown in Table 9 are based on the Conops for 2015 (Fig. 4).

Table 9. Types of Service Provided to Lunar Users

User Classes	Service Classes: Voice Tx	SDTV Tx	HDTV Tx	File Transer Tx	Telemetry Eng. Tx	Telemetry Med. Tx	Tracking Tx	Command Eng. Tx	Command Med. Tx	Voice Rx	SDTV Rx	HDTV Rx	File Transfer Rx	Telemetry Eng. Rx	Telemetry Med. Rx	Tracking Rx	Command Med. Rx	Command Eng. Rx
Lunar Surface Mobile Users																		
Astronaut (in EVA suit)	■	■			■	■	■			■						■	■	
VideoCam (hand-held or remote)		■	■	■	■		■						■					■
Rover		■	■	■	■		■	?					■			■		■
Lunar Surface Stationary Users																		
Surface Habitat or CEV	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Unattended Science Instrumentation		■	■	■	■		■						■			■		■
Surface Power System				■	■		■						■			■		■
Comm NOC	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Lunar Orbiting Users																		
CEV	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Lander	■	■	■	■	■		■	■		■	■	■	■	■		■		■
Earth Surface Users																		
Robotic MCC	■	■	■	■	■			■		■	■	■	■	■				■
Human Exploration MCC	■	■	■	■				■	■	■	■	■	■	■	■			
Navigation Support Facility	■			■				■		■			■	■				

Filled box implies service is used

Two studies were performed for Lunar Network in 2015. The first study treated the case where the requirement is for focused investigation of the south polar region (80-90º S latitude). The second study responded to ESMD's draft requirement to provide coverage for the entire lunar surface. Figure 16 shows the results of the first study. The combined score over all of the individual FOM scores for each of the candidate architectures is plotted against the cost estimate generated by the ACEIT/NAFCOM model. Cost is in units of "NAFCOM Model Dollars (NM$)" although the CERs are calibrated in actual US dollars ($M) to avoid the misimpression that total program cost is

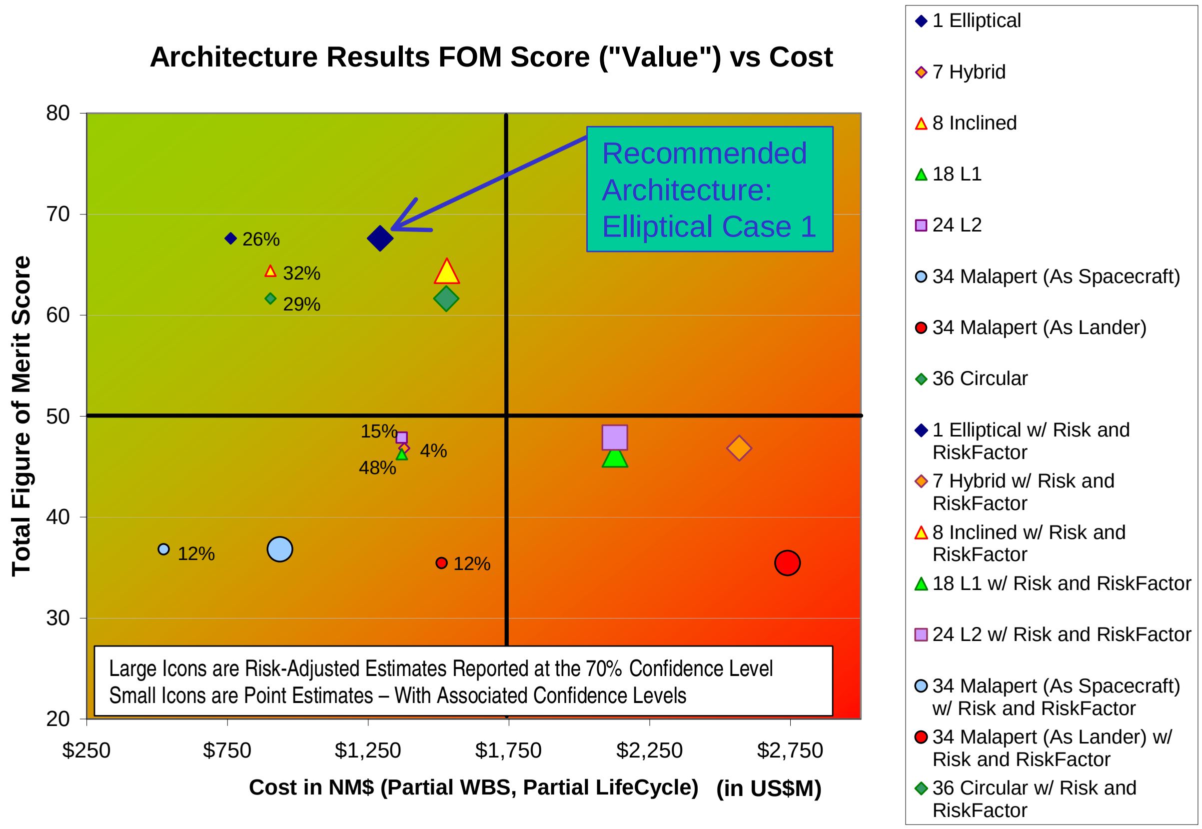


Figure 16. LN2015 Cost/Benefit Analysis for the Lunar South Pole Scenario

being estimated. Costs in these models are limited to capturing the essential elements of the WBS needed to discriminate between the candidate architectures (as defined in Fig. 3). To normalize the cost estimates across candidates that are defined at very different levels of fidelity and have different risks associated with the mission concept and/or technology assumptions, the point estimate for each candidate's cost model, based only on CERs driven by weight, power, and complexity, are adjusted for risk. Figure 16 shows both the unadjusted cost estimates with the calculated risk confidence level and the risk-adjusted cost estimate where all candidates' costs can be compared on an "apples-to-apples" basis at the same risk confidence level. A 70% confidence level was recommended by the OCFO for these studies. Figure 16 is divided into quadrants that show the highest benefit/lowest cost options in the upper left and the lowest benefit/highest cost options in the lower right.

The conclusion is that the polar elliptical constellation of two lunar relay satellites in one plane (Elliptical, case 1) provides the most cost effective solution to the lunar communication needs if the mission focuses on the south polar region. The risk adjustment shows that the point estimate cost of approximately 750M (NM$) is overly optimistic; the cost estimate is $1,250M when adjusted to give a 70% probability of successful delivery within budget. Two other candidates, the 70º inclined polar constellation of three satellites in one plane (Inclined, case 8) and the polar circular constellation of three satellites in one plane (Circular, case 36) provide about the same benefit while costing more due to the larger constellation size.

Two radically different cost estimates were obtained for the Malapert Station Lander concept. Using the same CERs as were used for the other candidates, which were all orbiting relay satellites, yields the lower risk-adjusted cost estimate of 870M (NM$). We investigated the hypothesis that landers cost significantly more than equivalent orbiters by generating an alternate set of CERs based on the extremely limited population of landers in the NAFCOM cost database (Mars Viking, Lunar Surveyor, Apollo Lunar Module, and Mars Pathfinder). This sample size is statistically insignificant and skewed by including a human rated mission, yet the cost estimate generated is so high (2,750M NM$) that it suggests that more attention needs to be paid to finding ways to better estimate the costs of landed elements.

The second study that changed the objective to full lunar coverage required evaluation of different constellations using different satellite designs in different orbits.

Design concepts had to meet the following requirements: a) 6 Voice channels; b) 600 Mbps return link from Moon to Earth; c) 200 Mbps forward link from Earth to Moon; d) Full, continuous coverage of the Moon from 90º N-90º S including the far side. The voice channels were handled using one full coverage UHF antenna. At any time, one satellite acts as the Earth/Moon relay while the others use crosslinks to feed the active relay satellite. One Ka-band 1m Moon/Earth antenna performs double duty for the Space Ground Link (SGL) and when not on the Earth relay satellite is used as a crosslink antenna. Three Ka band antennas on each satellite are each capable of receiving two 100 Mbps channels from the lunar surface. Each antenna is capable of transmitting up to 100 Mbps to the lunar surface. To implement this concept, three different design approaches were evaluated:

- TDRS Derivative: This was the same as one of the designs for first Lunar Relay 2015 study and used technologies at TRL 9 (operational).
- Evolved communication payload on an existing commercial bus: This concept used technologies at TRL 7-8, i.e., communication technology that is SOA – SOA+2 years on an Orbital Sciences Star-2 bus.
- "Next Generation" communication payload on a "Next Generation" bus: This was based on TRL 6-7 communication technology targeted at reducing mass by 1/3 to allow stacking 3 spacecraft on one Delta II ELV. Technologies included using Software Defined Radios and inflatable antennas.

The architecture classes used included:

- Polar Circular with two options: a) 6 satellites, 2 planes, 3 satellites per plane; b) 8 satellites, 2 planes, 4 satellites per plane
- Inclined Circular with two options: a) Inclination 52.2 deg, 6 satellites, 2 planes, 3 satellites per plane; b) Inclination 48.2 deg, 8 satellites, 2 planes, 4 satellites per plane
- Lang-Meyer with 4 inclined planes (58.9 deg) with 1 satellite/plane; 2 equatorial satellites
- Walker 5/5/1 with 5 inclined planes (43.7 deg) with 1 satellite/plane
- Polar + Equatorial Hybrid with two options: a) 2 planes, 3 satellites/plane, 2 in equatorial orbit; b) 2 planes, 3 satellites/plane, 3 in equatorial orbit (Fig. 17)

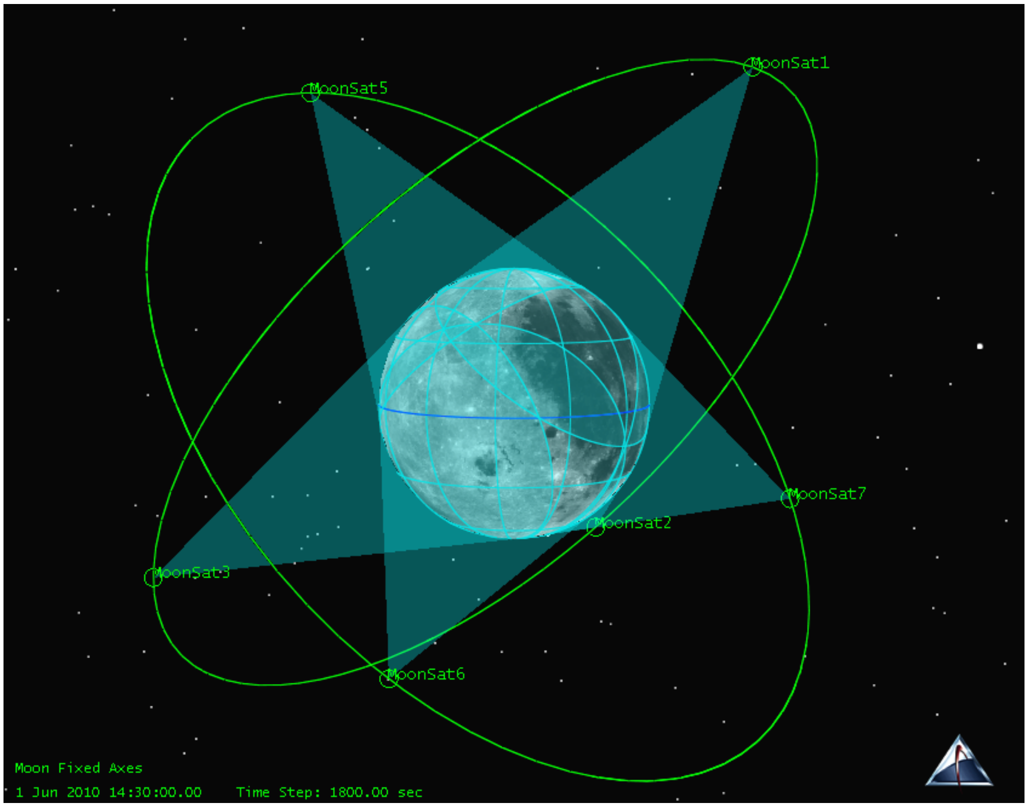


Figure 17. Example of Inclined Circular 6 Satellite 2 Plane Constellation for Full Lunar Coverage

The study reached several conclusions. Coverage depends on the number of satellites, number of planes, relative phasing of the planes, and inclination. But constellations for full coverage do not depend on orbital radius. Orbital radius determines the dwell time and angle of elevation at the Edge Of Coverage (EOC). Some types of orbits are more useful for full coverage than others. For example, polar orbits provide enhanced coverage of the poles while inclined and circular orbits provide more uniform global coverage. Elliptical orbits provide better focused regional coverage but worse global coverage. Continuous 100% lunar global coverage can be achieved with 5 or more satellites (Walker 5/5/1) but the 5 satellite case requires 5 planes with higher deployment risk and launch constraints. Also, the loss of one satellite equals the loss of a plane, so it is less fault tolerant. Several good candidates exist for global lunar coverage with 6 satellites in polar or inclined orbits. Eight satellites are not needed based on the anticipated data rates and volume.

The communication payload design needed to meet the SCAWG scenario (not an ESMD scenario) is small. The Next Generation design appears to offer the most cost effective solution at ~20% less than other candidates. However, the cost model assumed all new development on all options, thus overstating the cost when using the TDRS derivative and commercial Star bus. Our current ability to model and estimate the Ground Segment and Operations Phase costs is poor and requires further development.

Finally, the study concluded that full lunar coverage communications can be provided to meet ESS Spiral 2 requirements for $1.3-2.3B (Life cycle cost in FY05$ including 10 years of operations). The range in the cost estimate covers potential changes to requirements, modeling and analysis errors, and risk adjustments.

E. Mars Network (MN)

NASA is transforming data relay between Mars and Earth in this decade. The traditional approach of incorporating a communication subsystem with direct Earth/Mars links on every Mars mission is being replaced by a series of orbiters with dual missions to conduct science and to provide data relay and navigation services creating a local RF network around Mars. This network currently includes UHF relays on two NASA orbiters, Mars Global Surveyor (MGS) and Mars Odyssey (MO)[18], that are in low orbits selected to optimize the science instruments rather than relay performance. The network is augmented by UHF relays on the ESA Mars Express orbiter in 2004 and by the NASA Mars Reconnaissance Orbiter (MRO) in 2006. These spacecraft establish an initial Mars Network and have already demonstrated to the scientific community the value of proximity relay links over interplanetary direct links. The science team that is operating the Mars Exploration Rovers (MER) Spirit and Opportunity for the past year transitioned in the first two months of operation from using a mixture of Direct To Earth (DTE) links and relays through MGS and MO to almost total reliance on the relay links. Experience showed that the energy efficiency of the relays and the convenience of frequent passes and long contact times enabled them to improve their operations yielding greater scientific benefit. To date, more than 90% of rover data has been returned through relays (typically 100 Mb/sol). By using the same frequencies and CCSDS communication protocol, the European Mars Express was able to demonstrate the value of interoperability by sharing relay duties.

The year 2010 will mark another step in this evolution when the Mars Telecommunications Orbiter (MTO)[19] enters service and becomes the first interplanetary spacecraft whose primary mission is to provide telecommunications services to other missions. MTO will have high performance proximity relay (UHF and X-band) and Earth (X- and K_a-bands) telecommunications systems, and will demonstrate laser communications between Mars and Earth. While MTO carries 4 Centre National d'Etudes Spatiales (CNES) NetLanders for deployment, its primary mission is telecommunications and, consequently, it is placed into an orbit optimized for its relay communications mission. The concept for MTO and the Mars Laser Communication Demonstration (MLCD) is shown in Fig. 18. MTO will provide enhanced telecom services to science missions operating on the Martian surface, in the Martian atmosphere, and in orbit, including a) higher data rates, b) higher data volumes, c) increasing connectivity and d) flexible critical event coverage (e.g. during entry, descent and landing).

The MTO is a key element of expanding our human and robotic coverage of Mars as it enables future missions such as the Mars Science Laboratory (MSL) to eliminate large, heavy, power hungry antennas with primary communications though a UHF antenna capable of relaying 1 Gb/sol and an X-band receive Low Gain Antenna (LGA) (Fig 19). The MN evolves over the decade from 2010-2020 using each of the minimum energy launch windows (Fig 20) to fly ballutes and aerial vehicles as well as landers. With a mission life of 10 years, MTO's capabilities are driven by the union of the requirements for all of the Mars missions envisioned for the 2010-2020 time frame. A survey of the proposed missions for this time frame resulted in the data volumes shown in Fig. 21. These missions drive additional functionality into MTO to support autonomous rendezvous and docking, critical event monitoring, and navigation support for approach, landing, and surface transport.

In 2018 MTO's successor, MTO 2, is launched with even greater capabilities to support the growing science demands as well as the first landings by the human exploration program in the 2020-2030 time frame.

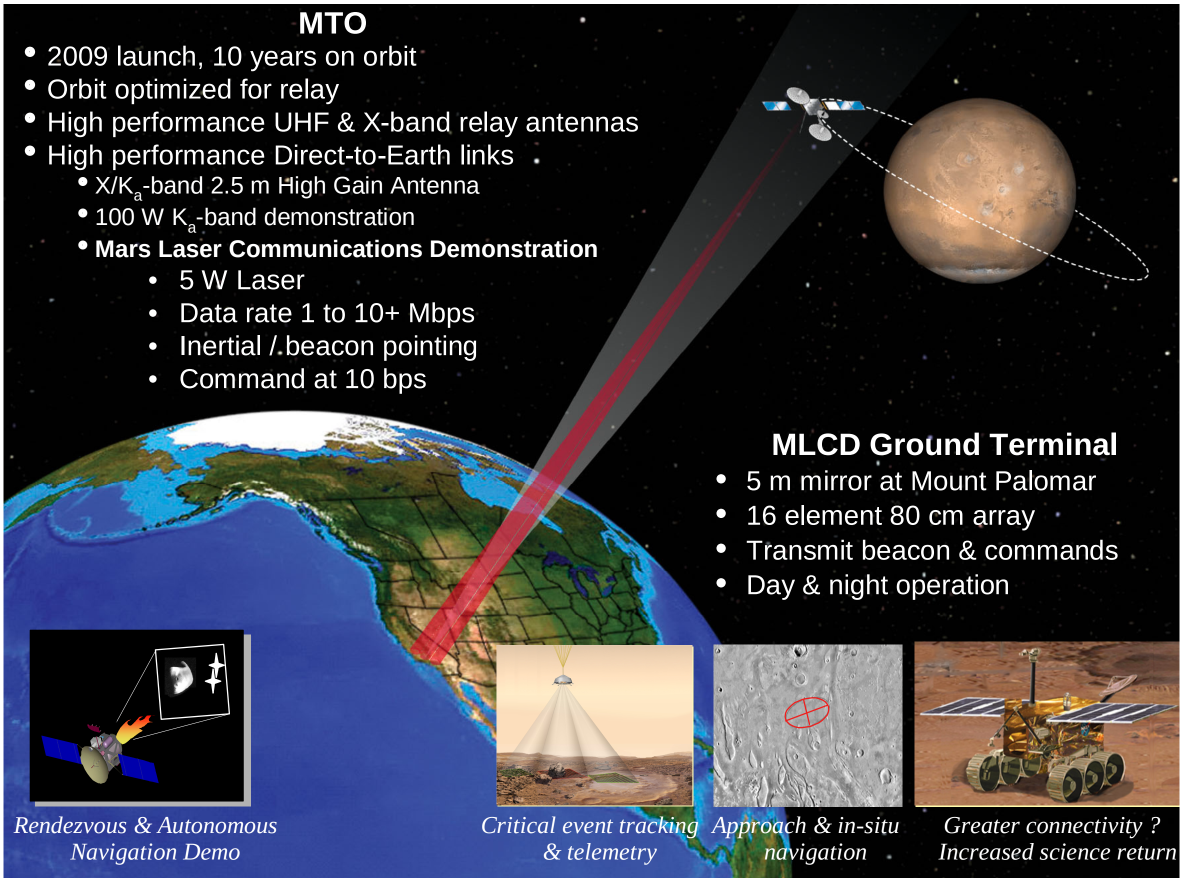


Figure 18. MTO and Mars Laser Communication Demonstration Concept

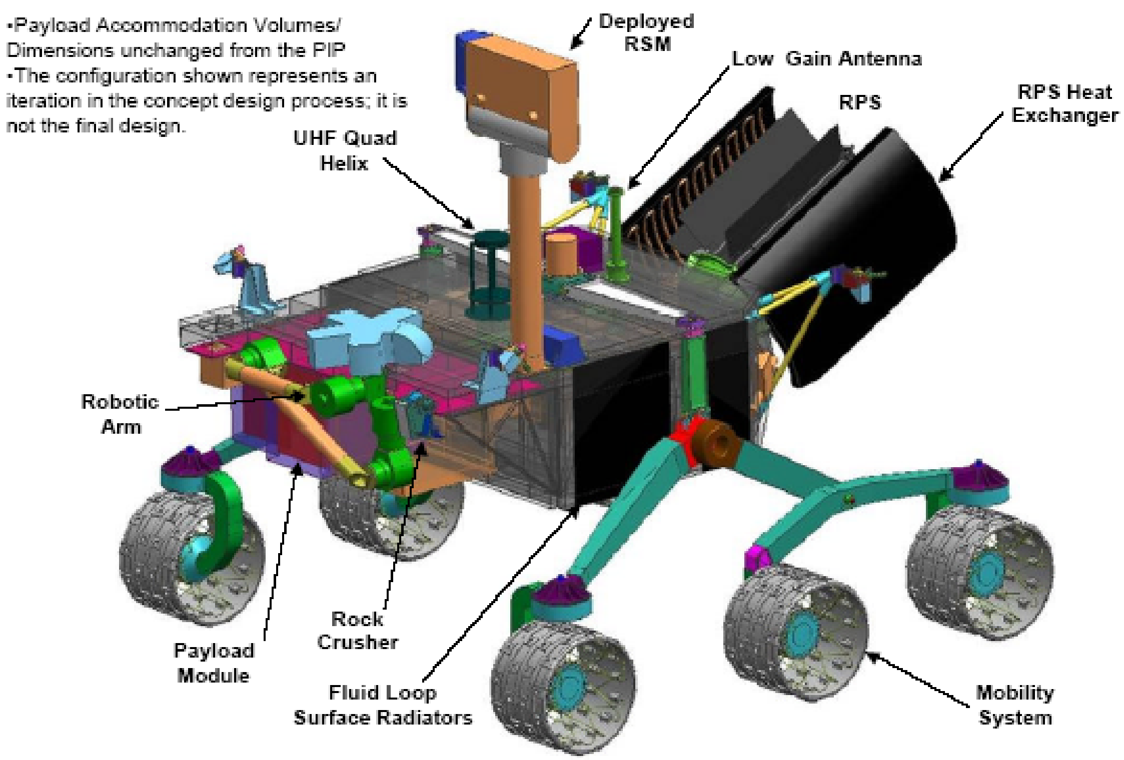


Figure 19. Mars Science Laboratory with UHF Quad Helix & X-band LGA

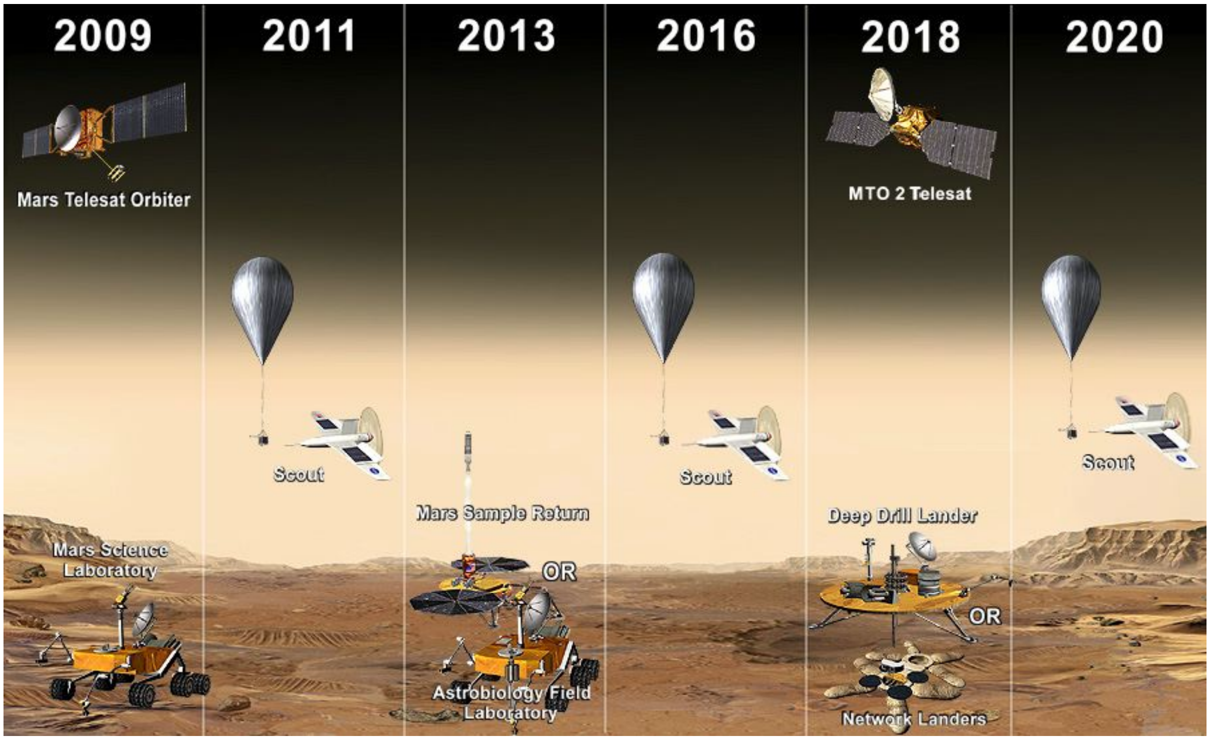


Figure 20. Evolution of the Mars Network from 2010-2020

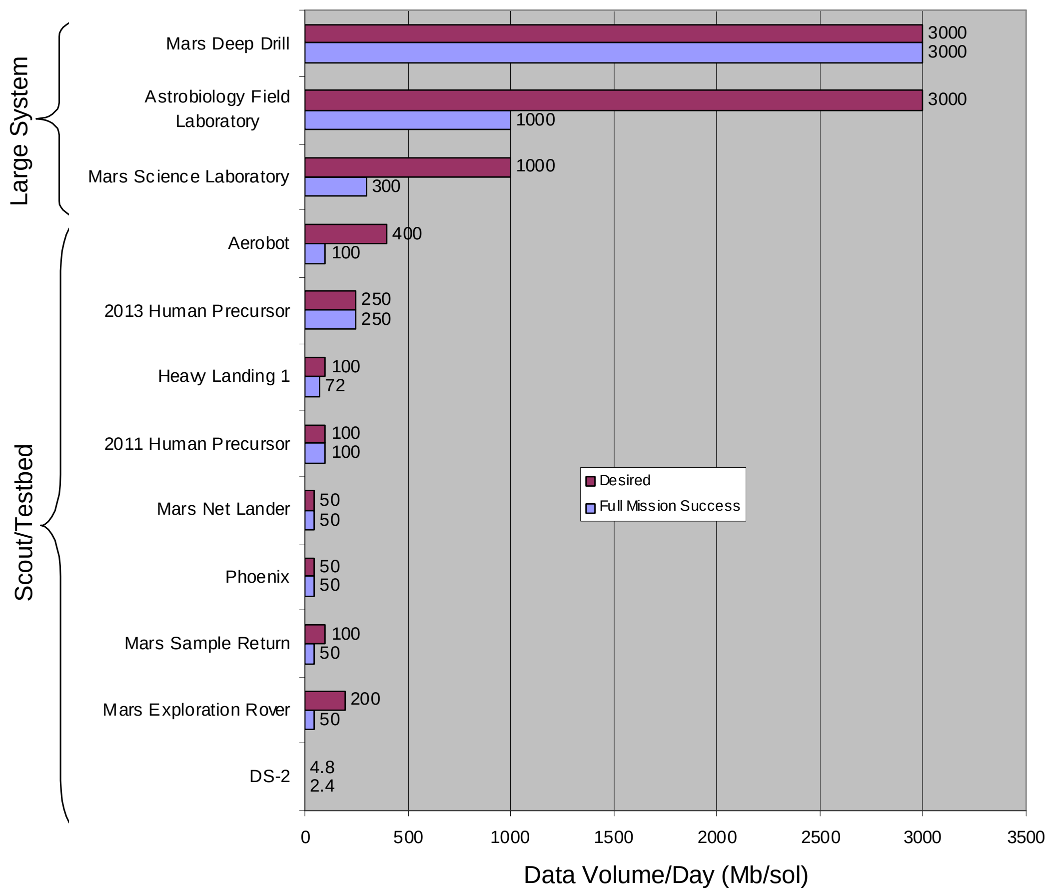


Figure 21. Projected Mars Relay Data Volume for 2010-2020

F. Rest Of Universe

Scientific missions to explore the Rest of the Universe are highly diverse in terms of the location(s) that the spacecraft have to reach to collect observations and the nature of the scientific questions to be answered with corresponding demands on sensors, communications, navigation, and mission operations. SMD and JPL track the projected missions and mission requirements and update their forecast annually. Figure 22 shows the current projections for US-led deep space missions. Support for international missions adds further requirements to this list. Collectively, these missions are expected to drive communications and navigation requirements up by nearly three orders of magnitude (1000x) over our capabilities in 2005. They drive half of the improvements required in the DSN. While all of these spacecraft require one or more direct links to Earth, not all of these missions are accommodated by DSN. Turning these mission concepts into real programs requires continuing efforts to translate fundamental research topics into realistic missions and developing the technology to design and build spacecraft that can close the links to Earth and deliver the data that enables the scientific community to probe the origins of life and the universe are ongoing tasks.

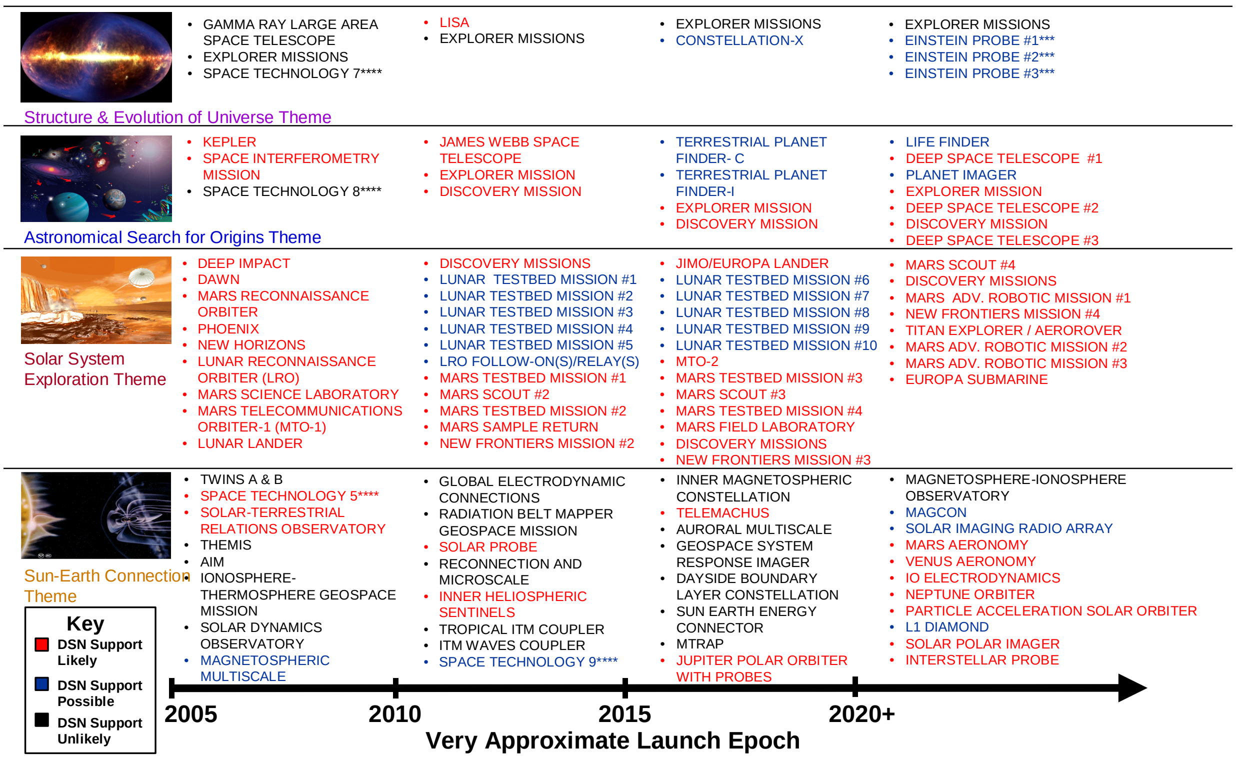


Figure 22. Projected Future US-led Deep Space Missions for 2005-2020+

VI. Plans for 2005

The SCAWG will finish the first round of activity wrapping up with integrating the architecture results across the solar system and over the entire 2010-2030 time period. Moving into the second round effort for the remainder of 2005 (through October), the SCAWG will synthesize ESMD In-Space Systems (Communications and Navigation) requirements that will be released in the summer of FY05 to further refine the SCA, in addition to the following work:

a) Refine the “Framework” architecture by considering newly evolving mission concepts and plans and any new communication architecture concepts identified for further investigation in the previous cycle.
b) Extend the framework architecture below the RF Spectrum level to define network structure and management and identification of standards to be used for communication protocols.
c) Refine the architecture to assure smooth evolution from one architecture stage to the next.
d) Expand the technology work area definitions by closely analyzing the TRLs and projecting TRL progression to enable infusion into the architecture.

Thus, the focus of our round 2 effort will be on repeating the studies over the time frames and locations performed in Round 1 with revisions based on lessons learned, changes in concepts and requirements, and tighter integration of the C&N Technology Roadmaps. Areas where shortcomings have been noted during Round 1 will be improved including: modeling and estimating costs for ground systems, documenting the SCA for easy reading and updating, building a database of ELV and spacecraft bus data, and developing methods for defining spacecraft designs (especially those farther in the future) in sufficient detail to support accurate discrimination between architectures and costing.

A third round in 2006 will further refine the architecture and technology roadmaps to assure alignment with the firming concepts and requirements for Exploration, Science, and Operations.

Throughout the architecture development process, the SCAWG will also provide support to the Communications and Navigation Capability Roadmap team. The C&N Capability Roadmap team is one of 15 Capability Roadmap teams and 13 Strategic Roadmap teams working throughout the NASA community to define our future. As the exploration vision is refined, the roadmapping efforts will be integrated to ensure the different scientific and technical communities are working along the same path, with shared requirements and clear definitions of relationships between the capability and strategic roadmaps.

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